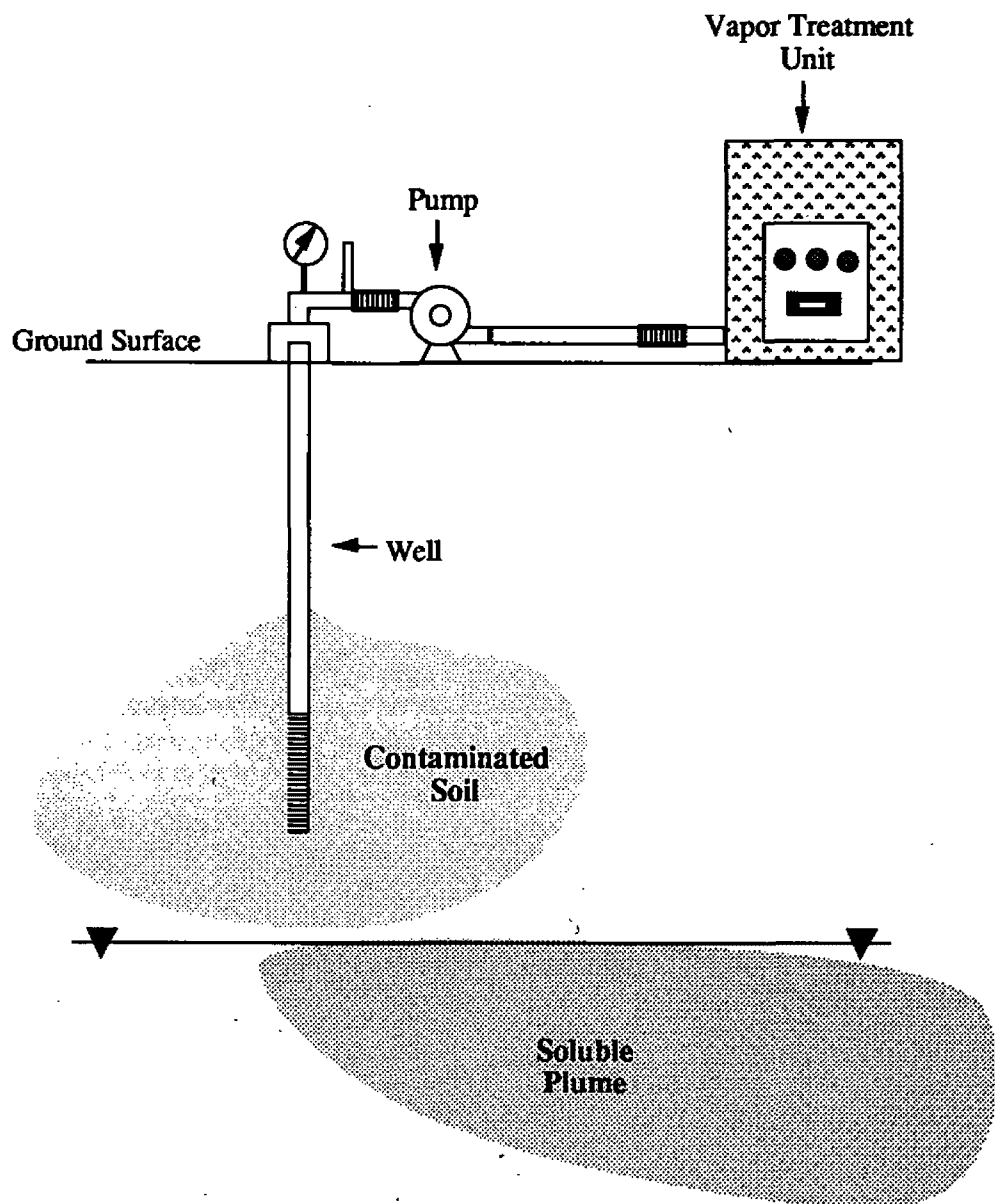




HyperVentilate Users Manual

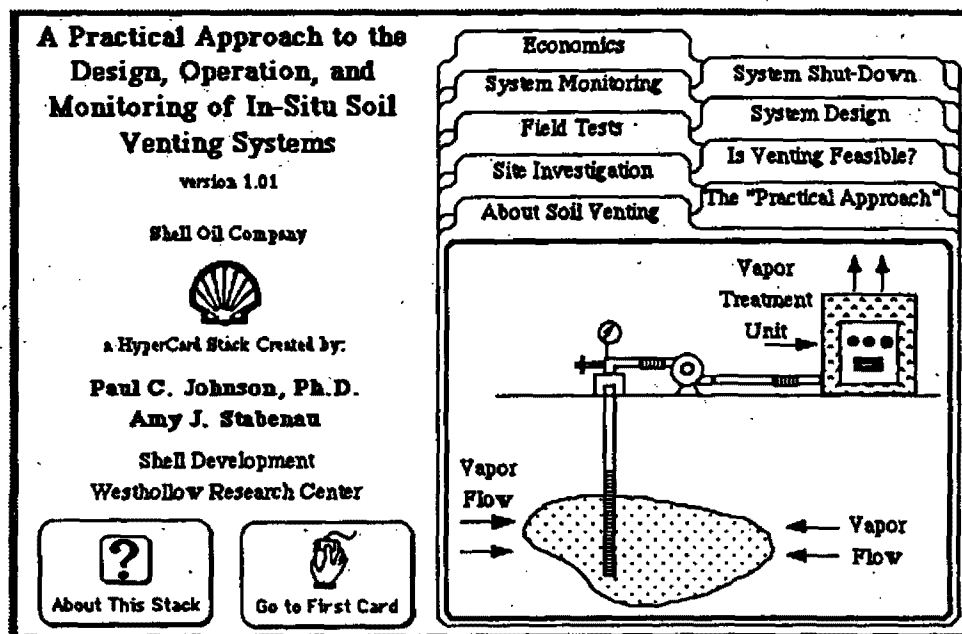
A Software Guidance System Created For Vapor Extraction Applications



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HyperVentilate Users Manual

A Software Guidance System Created for Vapor Extraction Applications



by

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Apple® Macintosh™ HyperCard™
compatible version 1.01

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Disclaimer

The HyperVentilate software package was completed under a Federal Technology Transfer Act Cooperative Research and Development Agreement between EPA and Shell Oil Company, signed in 1990.

EPA is facilitating the distribution of HyperVentilate because the Agency has found the software and manual to be helpful tools, especially in teaching users about in situ soil venting and in guiding them through a structured thought process to evaluate the applicability of soil venting at a particular site. EPA's Office of Underground Storage Tanks advocates the use of innovative cleanup technologies, and in situ soil venting is recognized as an effective remediation alternative for many underground storage tank sites.

HyperVentilate is based on the document titled, "A Practical Approach to the Design, Operation, and Monitoring of Soil Venting Systems" by P. C. Johnson, C. C. Stanley, M. W. Kemblowski, J. D. Colthart, and D. L. Byers, published 1990 by Shell Oil Company. The program asks a series of questions and forms a "decision tree" in an attempt to identify the limitations of in situ soil venting for soils contaminated with gasoline, solvents or other relatively volatile compounds.

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Please do not call the author and/or Shell with questions about the use or interpretation of results from this program.

Foreword

HyperVentilate is a software guidance system for vapor extraction (soil venting) applications. Initial development of this program occurred under the Apple Macintosh HyperCard environment, due to its programming simplicity, ability to incorporate text and graphics, and interfacing with other Macintosh programs (such as FORTRAN codes, etc.). The objective was to create a user-friendly software package that could be both educational for the novice environmental professional, and functional for more experienced users.

HyperVentilate *will not* completely design your vapor extraction system, tell you exactly how many days it should be operated, or predict the future. It *will* guide you through a structured thought process to: (a) identify and characterize required site-specific data, (b) decide if soil venting is appropriate at your site, (c) evaluate air permeability test results, (d) calculate the minimum number of vapor extraction wells, and (e) quantify how results at your site might differ from the ideal case.

HyperVentilate is based on the article "*A Practical Approach to the Design, Operation, and Monitoring of Soil Venting Systems*" by P. C. Johnson, C. C. Stanley, M. W. Kemblowski, J. D. Colthart, and D. L. Byers [Ground Water Monitoring Review, Spring 1990, p.159 - 178]. The software performs all necessary calculations and contains "help cards" that define the equations used, perform unit conversions, and provide supplementary information on related topics. In addition, a 62-compound user-updatable library (to a maximum of 400 compounds) is also included.

HyperVentilate version 1.01 for the Apple Macintosh requires an Apple Macintosh (Plus, SE, SE/30, II, IIX, or portable) computer equipped with at least 1 MB RAM (2 MB preferred) and the Apple HyperCard Software Program (v.2.0 or greater)

This manual is not intended to be a primer on soil venting (although the software is) and it is assumed that the user is familiar with the use of an Apple Macintosh personal computer.

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I. Introduction

In situ vapor extraction, or soil venting is recognized as an attractive remediation alternative for "permeable" soils contaminated with "volatile" compounds. As Figure 1 illustrates, vapors are removed from extraction wells, thereby creating a vacuum and vapor flow through the subsurface. Until the residual contamination is depleted, contaminants will volatilize and be swept by the vapor flow to extraction wells. While its use has been demonstrated at service stations, Superfund sites, and manufacturing locations (see Hutzler et al. [1988] for case study reviews), vapor extraction systems are currently designed more by intuition than logic. In fact, many systems are installed at sites where the technology is not appropriate.

"A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems" [Johnson et al. 1990a - see Appendix G] is a first attempt at creating a logical thought process for soil venting applications. The article, which is based on earlier results of Thornton and Wootan [1982], Marley and Hoag [1984], Johnson et al. [1990], and discussions with several of these authors, describes a series of calculations for determining: (a) if soil venting is appropriate at a given site, (b) limitations of soil venting, and (c) system design parameters, such as minimum number of extraction wells and potential operating conditions.

HyperVentilate is a software guidance system based on the Johnson et al. [1990a] article. The software performs all necessary calculations and contains "help cards" that define the equations used, perform unit conversions, and provide supplementary information on related topics. In addition, a 62-compound updatable chemical library (to a maximum of 400 compounds) is included.

Initial development of this program occurred under the Apple Macintosh HyperCard environment, due to its programming simplicity, ability to incorporate text and graphics, and interfacing with other Macintosh programs (such as FORTRAN codes, etc.). The objective was to create a user-friendly software package that could be both educational for the novice environmental professional, and a functional tool for more experienced users. The OASIS [1990] system created at Rice University for groundwater contamination problems is another excellent example of the use of HyperCard as a technology transfer tool.

This document is a users manual for **HyperVentilate**. It contains sections describing the installation and operation of the software. During the development of **HyperVentilate**, the goal was to create a guidance system that could be used with little or no instruction. Experienced Apple Macintosh users, therefore, can load and explore the capabilities of this program after glancing at the "*Loading HyperVentilate Software*" section. Those users that are less comfortable about exploring software without a manual are encouraged to read through it once, and work through the sample problem. It is intentionally brief, and a beginner should be able to navigate through the system in less than a couple hours. It is assumed that the user has some previous Macintosh experience. If not, consult a Macintosh users manual for a quick tutorial.

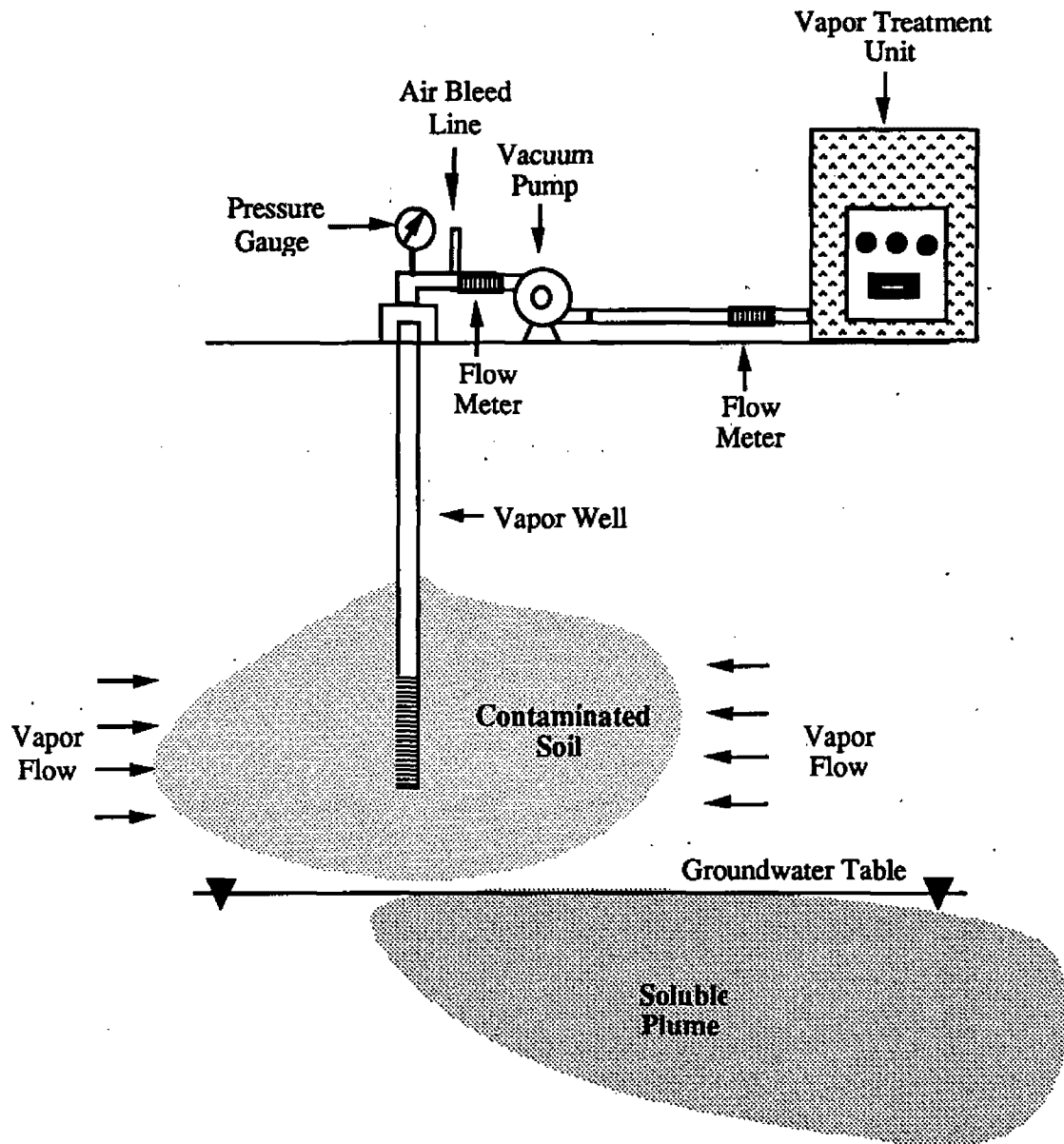


Figure 1. Schematic of a typical vapor extraction operation.

II. Definition of Some Terms Appearing in this Manual

button	- an object on a "card" that causes some action to be performed when "clicked" on
card	- an individual screen that you view on your monitor
click	- refers to the pressing and releasing of the button on your mouse
drag	- refers to holding down the mouse button while moving the mouse
field	- a text entry location on a "card"
HyperCard	- a programming environment created by Apple Computer, Inc.
mouse	- the device used to move the cursor within your monitor
select	- refers to "dragging" the cursor across a "field"
stack	- a group, or file, of "cards"

III. Software/Hardware Requirements

Apple Macintosh HyperVentilate version 1.01 requires an Apple Macintosh (or equivalent) computer equipped with at least 1 MB RAM (2 MB preferable), a hard disk, and the Apple HyperCard Software Program (v 2.0). Check to make sure that your system software is compatible with your version of HyperCard.

IV. Loading HyperVentilate Software

HyperVentilate is supplied on an 800 kB double-sided, double density 3.5" diskette. Follow the instructions listed below to insure proper operation of the software.

- 1) Insert the HyperVentilate disk into your computer's floppy drive. The HyperVentilate disk should contain the files:
 - "Soil Venting Stack"
 - "Soil Venting Help Stack"
 - "System Design"
 - "Air Permeability Test"
 - "Aquifer Characterization"
 - "Compound List Update"
 - "HypeVent"
 - "f77.rl"
 - 2) Copy these files onto your hard disk. They must be copied into the folder that contains the "HyperCard" program, or else the software will not operate properly.
 - 3) Eject the HyperVentilate disk
-

V. Using HyperVentilate

The authors of **HyperVentilate** intend it to be an application that requires little pre-training for the user. It is mouse-driven and instructions are included on each card, so please take the time to read them when you first use **HyperVentilate**.

This section of the users manual is divided into three subsections. Start-up instructions are given in the first, basic features of the cards are described in the second, and a sample exercise is presented in the third. For reference, copies of all cards, as well as more details on each are given in Appendices A through F.

V.1. Starting HyperVentilate

- 1) Those users with color monitors should use the "Control Panel" (pull down the "Ⓜ" menu and select "Control Panel", then click on the "Monitors" icon) to set their monitors to black and white, and two shades of grey.
 - 2) To avoid unnecessary "card-flipping", set the "Text Arrows" option in your "Home" stack "User Preferences" card to on. You can get to this card from within any HyperCard application by selecting "Home" under the "Go" menu. This will take you to the first card in the "Home" stack. At this point click on the left-pointing arrow and the "User Preferences" card will appear on your screen. Then click on the square to the left of "Text Arrows" until an "X" appears in the square.
 - 3) **HyperVentilate** is started by double-clicking on the "Soil Venting Stack" file icon from the Finder (or Desktop), or by choosing "Open" under the "File" menu (*Note that using a more advanced version of HyperCard than the one under which this system was developed (v 2.0) may require you to first "convert" each of the seven HyperCard stacks contained in HyperVentilate*).
 - 4) Your monitor should display the card shown in Figure 2. Note that there are a number of buttons on this card; there are two at the lower left corner, and then each file folder tab is also a button (some cards may contain less obvious "hidden" buttons; try clicking on the authors name on the title card for example). Clicking on any of these will take you to another card. For example, clicking on the "About This Stack" button will take you to the card shown in Figure 3, which gives a brief description about the use of buttons and fields. Read this card well.
 - 5) Explore for a few minutes. Try to see where various buttons will take you, try entering numbers in fields, or play with calculations. Again, just remember to read instructions given on the cards.
-

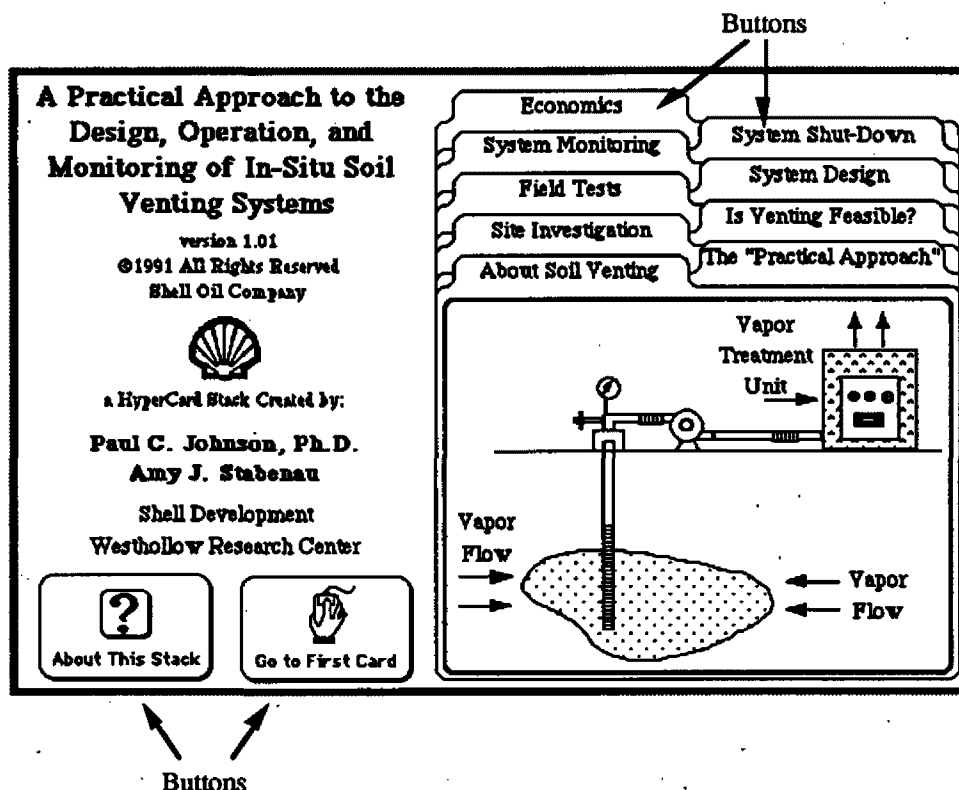


Figure 2. First Card of the "Soil Venting Stack" stack.

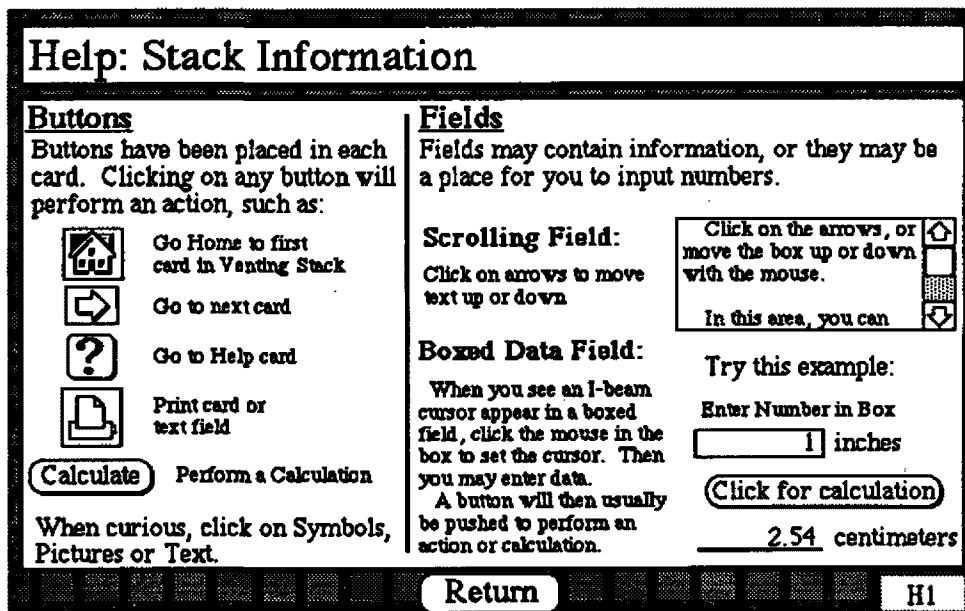


Figure 3. Card H1 of the "Soil Venting Help Stack" stack.

V.2. General Features of Cards

Figures 4 and 5 are examples of cards from the "Soil Venting Stack" stack and "System Design" stack. There are a few general features of these cards that users should understand:

- Each card (with the exception of the first card of the "Soil Venting Stack" stack) has been numbered for easy reference with the printouts given in Appendices A through F. In the "Soil Venting Stack" these numbers appear in the bottom center of each card (i.e. number "3" in Figure 4). In other stacks these numbers appear at either the top or bottom corners of the card (i.e. "SD1" in Figure 5).
- Arrow buttons are included at the bottom of some cards. Clicking on right-pointing arrow will advance you to the next card in the stack; clicking on the left-pointing arrow will take you in the opposite direction.
- The identifying card numbers in the "Soil Venting Stack" stack are also fields into which text can be typed. You can skip to other parts of the "Soil Venting Stack" stack by selecting this field, typing in the card number of your destination (within the "Soil Venting Stack"), and then hitting the "return" key.
- Many cards have a house button in the lower left corner. Clicking on this button will take you to the first card of the "Soil Venting Stack" stack, which is the card displayed at start-up (see Figure 2).

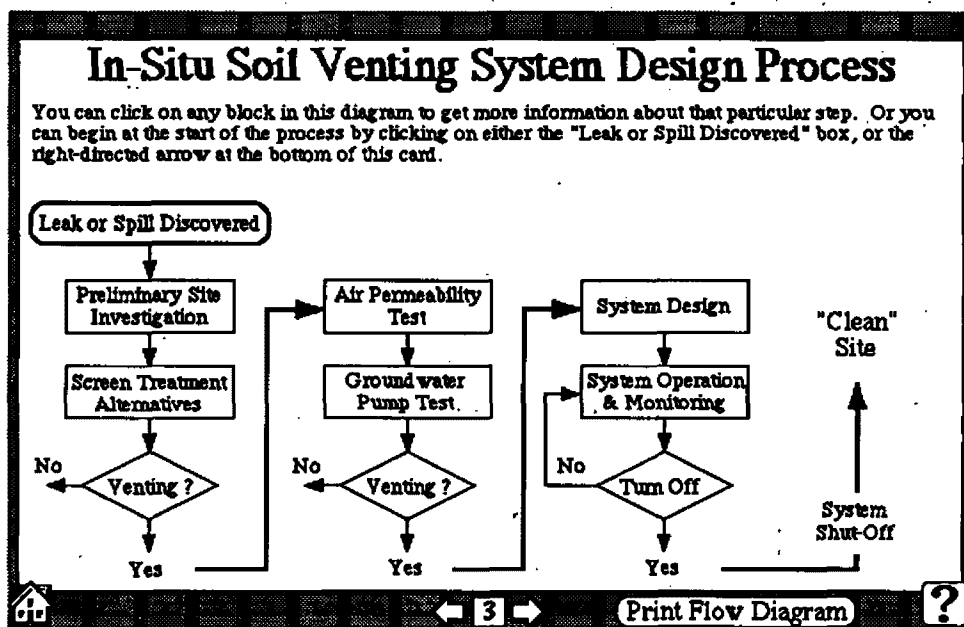


Figure 4. Card 3 of the "Soil Venting Stack" stack.

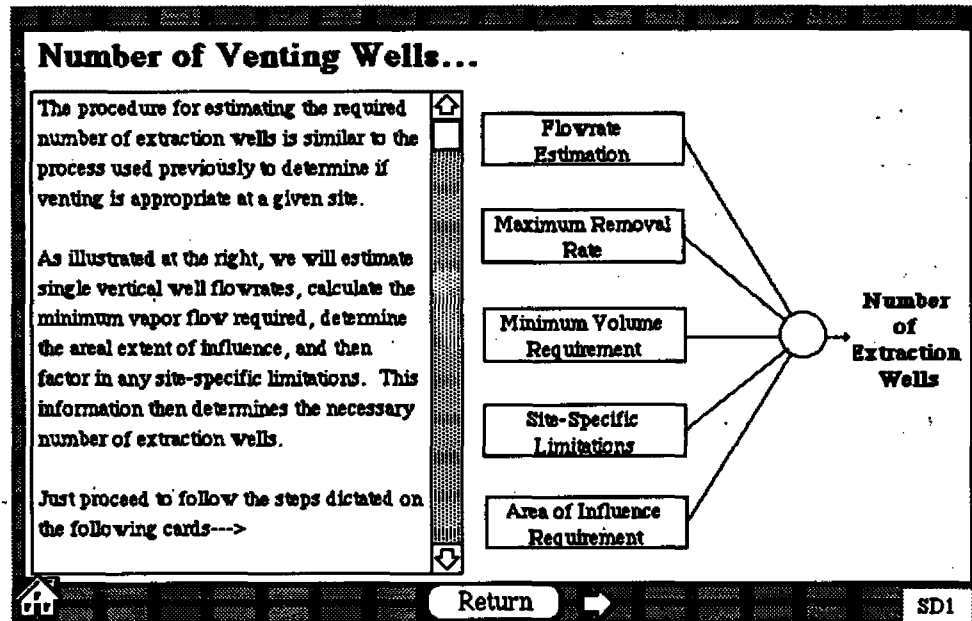


Figure 5. Card SD1 of the "System Design" stack.

V.3. Sample Problem Exercise

In the following a sample problem is executed in excruciating detail. Those not wishing to work along with the example are encouraged to utilize Appendices A through F as references for more details on the less obvious functions of some cards.

This "Sample Problem Exercise" is divided into to four subsections that address: navigating through **HyperVentilate** (§V.3.1), screening sites to see if soil venting is an appropriate technology (§V.3.2), interpreting air permeability test data (§V.3.3), and guidance for designing soil venting systems (§V.3.4).

V.3.1 Navigating Through HyperVentilate

- Step 1: Location: The "Desktop" or Finder.
 Action: Start-up **HyperVentilate** by double-clicking on the "Soil Venting Stack" icon, or click once on this icon and then choose "Open" from the "File" menu.
 Result: **HyperVentilate** will start-up and display the title card (Figure 2).
- Step 2: Location: Title Card of the "Soil Venting Stack" stack.
 Action: Click on the "About This Stack" button.
 Result: You are now at card H1 of the "Soil Venting Help Stack" stack (Figure 3).

- Step 3: Location: Card H1 of the "Soil Venting Help Stack" stack.
 Action: Play with the buttons and scrolling field. Practice entering a number in the field in front of "inches". Place the cursor in the box. It will change from a hand to an "I-bar" as it enters the field. Hold down the mouse button and drag the I-bar across the entry, which will become hilited. Now type in another number, or hit the delete key. Practice until you feel comfortable selecting text and entering numbers. Then click on the "Click for Calculation" button. When you are done practicing, click on the "Return" button.
 Result: Return to the title card of the "Soil Venting Stack" (Figure 2).
- Step 4: Location: Title Card of the "Soil Venting Stack" stack.
 Action: Click on the "Economics" file folder tab.
 Result: You are now at card 27 of the "Soil Venting Stack" stack. Take a quick glance at this card, which is displayed in Figure 6.
- Step 5: Location: Card 27 of the "Soil Venting Stack" stack.
 Action: Click on the "House" button in the lower left corner.
 Result: You are back at the title card (Figure 2).
- Step 6: Location: Title card of the "Soil Venting Stack" stack.
 Action: Click on the "Go to First Card" button.
 Result: You are now at card 1 of the "Soil Venting Stack" stack (Figure 7).

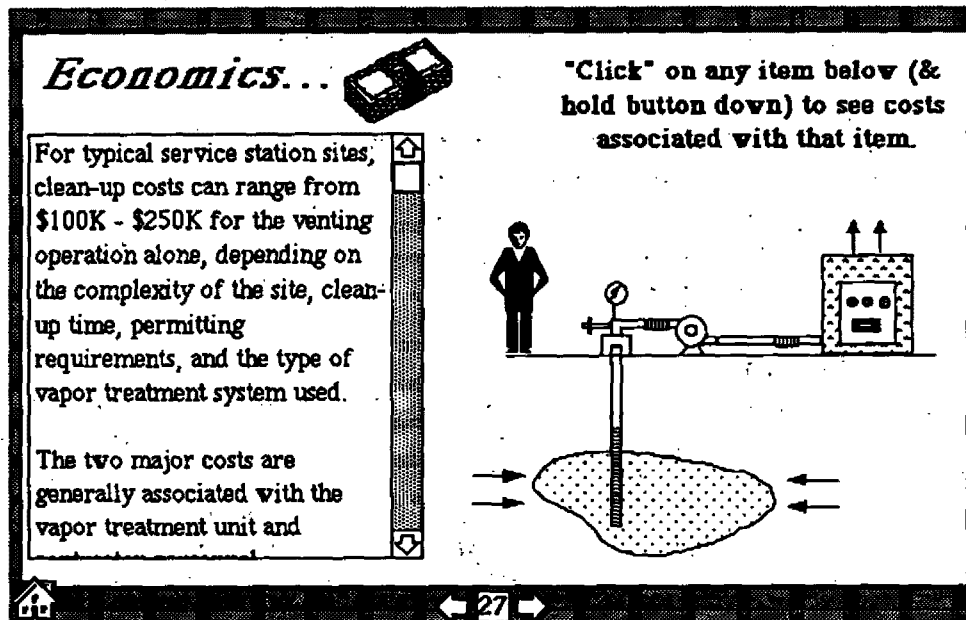


Figure 6. Card 27 of the "Soil Venting Stack" stack.

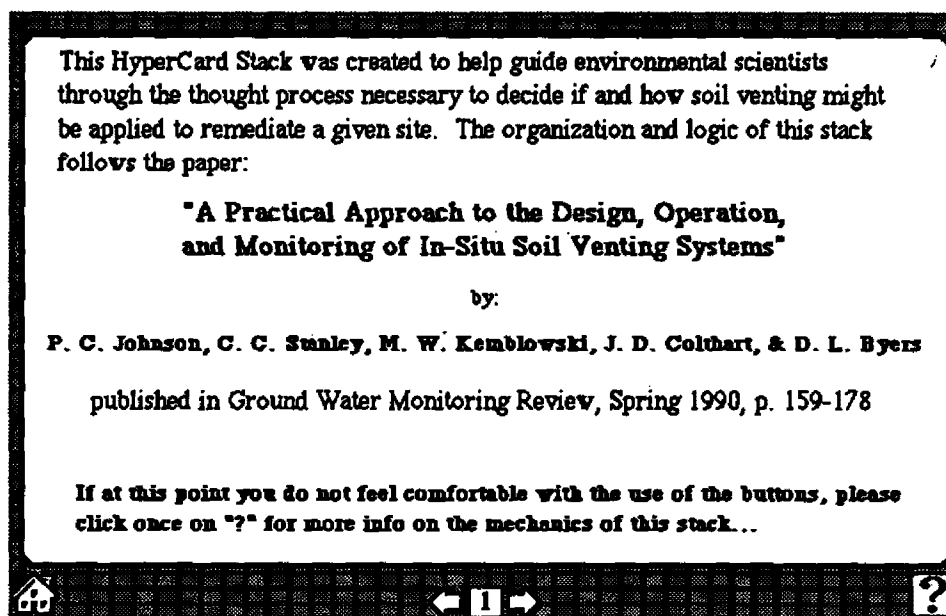


Figure 7. Card 1 of the "Soil Venting Stack" stack.

- Step 7: Location: Card 1 of the "Soil Venting Stack" stack.
Action: Click on the right-pointing arrow.
Result: You are now at Card 2 of the "Soil Venting Stack" stack (Figure 8).
- Step 8: Location: Card 2 of the "Soil Venting Stack" stack.
Action: Read the text, and click on the "down" and "up" arrows on the displayed text field under *"About Soil Venting..."* to make the field scroll. Then click on the left-pointing arrow at the card bottom.
Result: You are now back at card 1 of the "Soil Venting Stack" (Figure 7).
- Step 9: Location: Card 1 of the "Soil Venting Stack" stack.
Action: Click on the right pointing arrow.
Result: You are again at card 2 of the "Soil Venting Stack" stack (Figure 8). By now you should feel comfortable using the left- and right-pointing arrows to travel through the stack.
- Step 10: Location: Card 2 of the "Soil Venting Stack" stack.
Action: Click on the "?" button in the lower right corner of the card. This button indicates that there is a "Help" card containing additional information.
Result: You are now at card H2 of the "Soil Venting Help Stack" stack (Figure 9). Scroll through the list of references, then click on the "Return" button to return to card 2 of the "Soil Venting Stack" stack.

At this point you should feel comfortable navigating around in HyperVentilate.

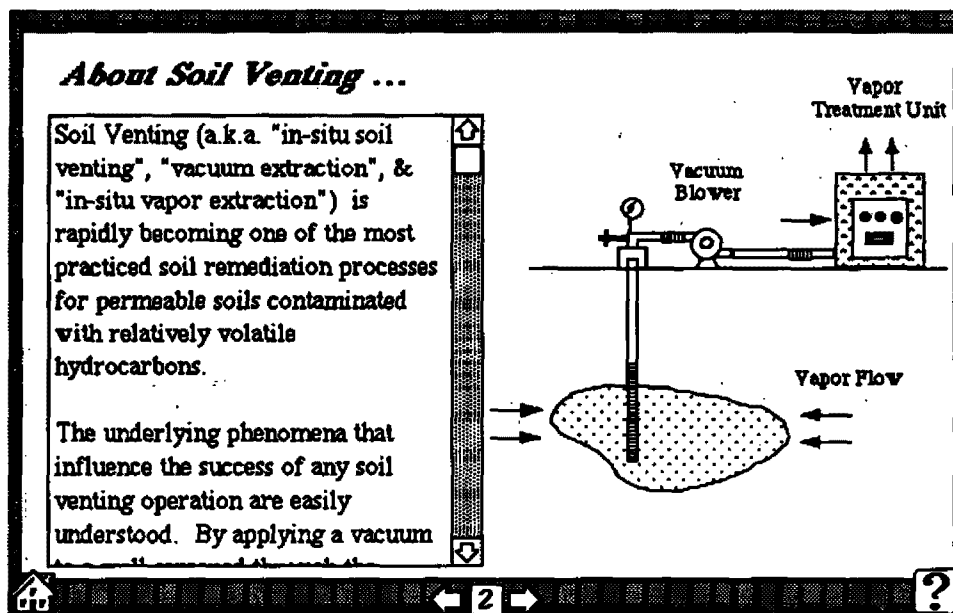


Figure 8. Card 2 of the "Soil Venting Stack" stack.

Help: About Soil Venting

More information about soil venting can be found in the following articles:

M. C. Marley and G. E. Hoag, Induced Soil Venting for the Recovery/Restoration of Gasoline Hydrocarbons in the Vadose Zone, NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, TX, 1984.

P. C. Johnson, M. W. Kemblowski, and J. D. Colhart, Practical Screening Models for Soil Venting Applications, NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, TX, 1988.

N. J. Hutzler, B. E. Murphy, and J. S. Gierke, State of Technology Review: Soil Vapor Extraction Systems, U.S.E.P.A., CR-814319-01-1, 1988.

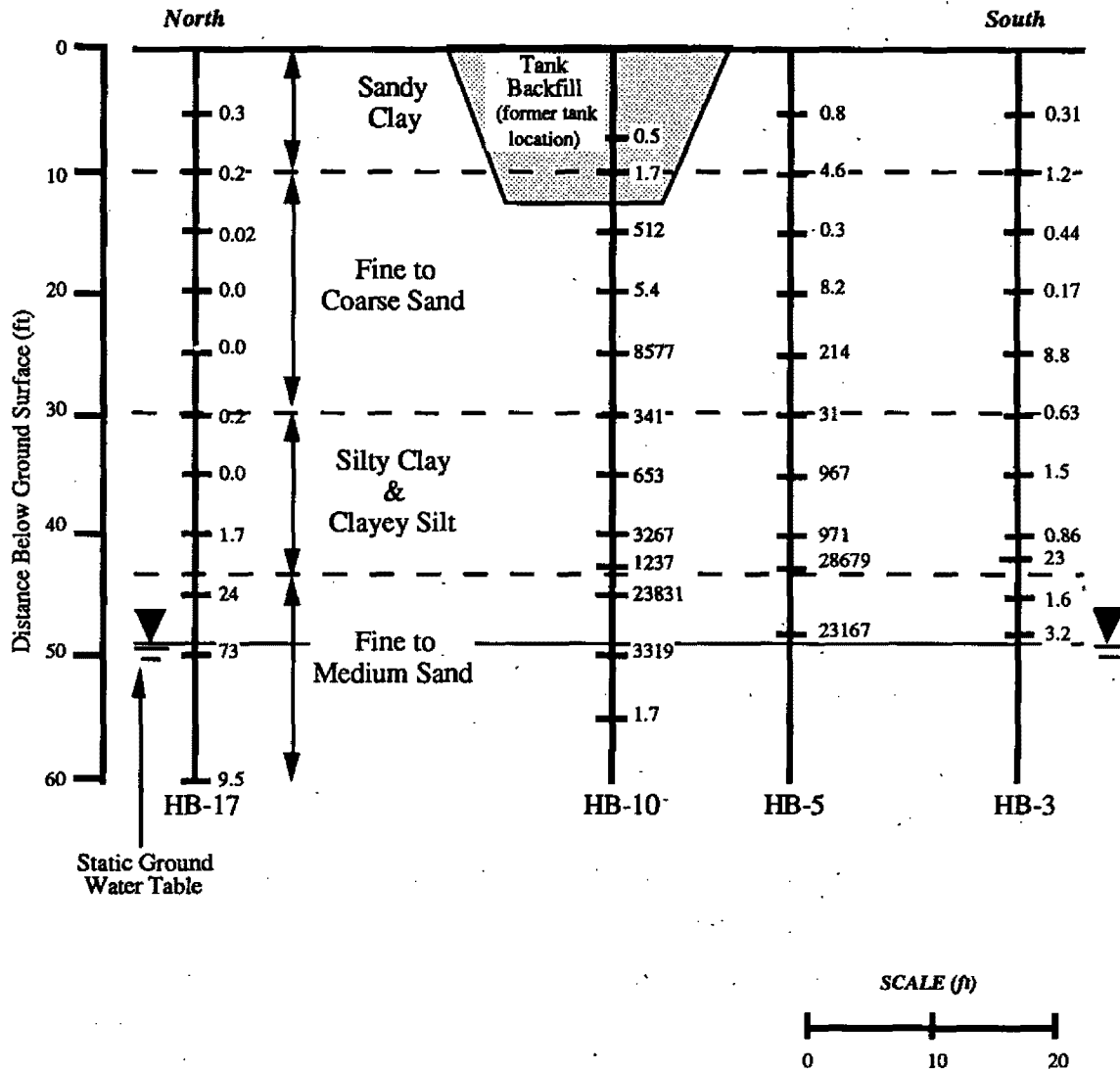
D. J. Wilson, A. N. Clarke, and J. H. Clarke, Soil Clean-up by in-situ Aeration. I. Mathematical Modelling, Sep. Science Tech., 23:991-1037, 1988.

H2 Return Print References

Figure 9. Card H2 of the "Soil Venting Help Stack" stack.

V.3.2 Sample Problem Exercise - Is Venting Appropriate?

In §V.3.2, you will work through an example problem to illustrate how one might decide if venting is appropriate at any given site. For the purpose of this example we will use the example site information given in Figure 10.



Contamination Type: Weathered Gasoline

Figure 10. Sample site data (Johnson et al. [1990a]). Total petroleum hydrocarbons (TPH) [mg/kg] values are noted for each boring.

Using your newly developed navigational skills and the right pointing arrow located at the bottom of each card, slowly step your way through the stack until you reach card 7 of the "Soil Venting Stack" stack (Figure 11). Take your time to read the text and "Help" cards associated with each card along the way.

- Step 1: Location: Card 7 of the "Soil Venting Stack" stack.
 Action: Read this card. It explains the process that you will use to decide if venting is appropriate. Then advance to card 8 of the "Soil Venting Stack" stack.
 Result: You are now at card 8 of the "Soil Venting Help Stack" stack (Figure 12).
- Step 2: Location: Card 8 of the "Soil Venting Help Stack" stack.
 Action: Read the instructions on this card. Take the time to read the information on the two "Help" cards: "Info about Calculation" and "About Soils (& Unit Conversions)".

Now we will evaluate the efficacy of applying in situ soil venting to the lower soil zone (45 - 50 ft below ground surface) in Figure 10, which is composed of fine to medium sands. It also is the zone of highest hydrocarbon residual levels (>20000 mg/kg TPH in some areas).

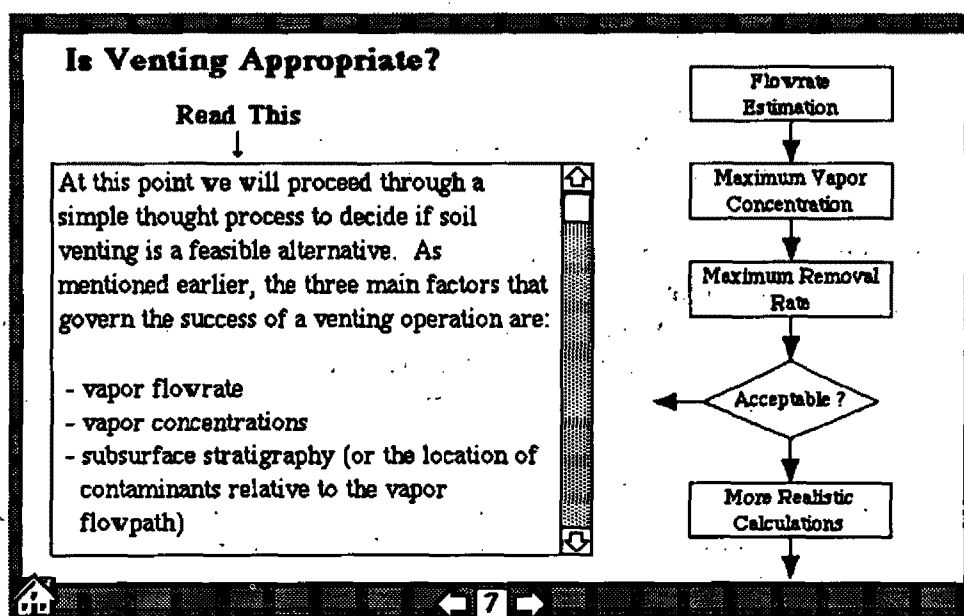


Figure 11. Card 7 of the "Soil Venting Stack" stack.

Flowrate Estimation:

☐ Medium Sand
☒ **Fine Sand**
☐ Silty Sand
☐ Clayey Silts
☐ Input Your Own Permeability Range
 Permeability Range (darcy)
 to

Well Radius in
 Radius of Influence ft
 Interval Thickness* ft

-->Calculate Flowrate Ranges<--

*thickness of screened interval, or permeable zone (whichever is smaller).

- 1) Choose Soil Type, or
Optional - Enter your own permeability values (darcy)
- 2) Enter Well Radius (in)
- 3) Enter Radius of Influence (ft) & Interval Thickness*
- 4) Optional - Enter your own well vacuum (406" = max)
- 5) Click button to calculate Predicted Flowrate Ranges

Predicted Flowrate Ranges

Well Vacuum P_w (in H_2O)	Flowrate (SCFM) (single well)		Flowrate (SCFM) (single well)
5	0.33	to	3.32
10	0.66	to	6.59
20	1.30	to	13.02
40	2.54	to	25.38
60	3.71	to	37.09
120	6.83	to	68.27
200	10.07	to	100.66

About Soils (& Unit Conversions)

 8

 Info about Calculation

Figure 12. Card 8 of the "Soil Venting Stack" stack.

- Step 3:** **Location:** Card 8 of the "Soil Venting Stack" stack.
 Action: Choose the "Fine Sand" soil type, and enter:
 well radius = 2 in
 radius of influence = 40 ft
 interval thickness = 6.6 ft
 user input vacuum = 200 in H_2O
 into the appropriate fields, then click on the
 "-->Calculate Flowrate Ranges<--" button.
 Result: The flowrate ranges are calculated and displayed. Your screen
 should now look like Figure 12. The calculated values are estimates
 of the flowrate to a single vertical well (and are only valid estimates
 when your conditions are consistent with the assumptions built into
 the calculation - see Johnson et al. [1990a, b] for more details).
- Step 4:** **Location:** Card 8 of the "Soil Venting Stack" stack.
 Action: Click on the right pointing arrow to advance to card 9. Read the
 information on this card, then advance to card 10
 Result: You are now at card 10 of the "Soil Venting Stack" stack (see Figure
 13).
- Step 5:** **Location:** Card 10 of the "Soil Venting Stack" stack.
 Action: Assume that the soil temperature at our sample site is 18° C. Enter
 this value in the appropriate field, then hit the "return" key. This
 action clears all values from the other fields.

Vapor Concentration Estimation - Calculation

1 Type in Temperature (°C) (hit <return>) 18

Click to Enter Composition of Contaminant ☐ Enter Distribution
2 or ☐ "Fresh" Gasoline
 Choose one of the Default Distributions ☒ "Weathered" Gasoline

3 Click to View Distributions, (optional) View Distributions

4 Click to Perform Calculations ☒ Perform Calculations

Results:
Sum of Mass Fractions 1.00000
Calc. Vapor Pressure 0.05784 atm
Calc. Vapor Concentration 203.94878 mg/l

How Do I Measure a Distribution? ← 10 → About Calculation Print Card

Figure 13. Card 10 of the "Soil Venting Stack" stack.

H16

Help: Compound List

"Weathered" Gasoline

View Only Mode

#	Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure (atm) @ 18 °C
1	propane	0.00	44.1	8.04673
2	isobutane	0.00	58.1	2.75865
3	n-butane	0	58.1	1.97431
4	trans-2-butene	0	56.1	1.84196
5	cis-2-butene	0	56.1	1.67019
6	3-methyl-1-butene	0	70.1	0.88399
7	isopentane	0.0069	72.2	0.73146
8	1-pentene	0.0005	70.1	0.64989
9	2-methyl-1-butene	0.0008	70.1	0.62093
10	2-methyl-1,3-butadiene	0.0000	68.1	0.60914

0.99628 = Sum of Mass Fractions
 (should be =1)

How Do I Measure a Distribution? Return to Vapor Conc. Estimation Card Print Lists

Figure 14. Card H16 of the "Soil Venting Help Stack" stack.

At this site the residual hydrocarbon is a "weathered" gasoline, so choose this selection from the three composition options listed. The "Fresh" and "Weathered" gasoline selections correspond to pre-programmed compositions that are useful for estimation purposes. If you knew the composition of your residual, then you could enter it by selecting the "Enter Distribution" option. Click on the "View Distributions" button to take a look at the compound library and the pre-specified composition of "weathered" gasoline.

Result: You are now at card H16 of the "Soil Venting Help Stack" stack (see Figure 14).

Step 6: Location: Card H16 of the "Soil Venting Help Stack" stack.

Action: View the library and pre-specified composition: If you are interested, explore some of the help cards. Then click on the "Return to Vapor Conc. Estimation Card" button to return to card 10 of the "Soil Venting Stack" stack.

Result: You are now at card 10 of the "Soil Venting Stack" stack (Figure 13).

Step 7: Location: Card 10 of the "Soil Venting Stack" stack.

Action: Click on the "Perform Calculations" button.

Result: **HyperVentilate** calculates the maximum possible vapor concentration corresponding to the specified composition and temperature. The results are displayed in Card 10 of the "Soil Venting Stack" stack, which should now look like Figure 13.

Step 8: Location: Card 10 of the "Soil Venting Stack" stack.

Action: Using the right-pointing arrow button, advance to card 11 of the "Soil Venting Stack" stack. Take the time to read the text, then click on the "Calculate Estimates" button

Result: You are at card 12 of the "Soil Venting Stack" stack. The calculated flowrates and maximum possible removal rates are displayed along with an updated list of the input parameters that you have entered. Your screen should look like Figure 15, if you have chosen the "lb/d" units.

Step 9: Location: Card 12 of the "Soil Venting Stack" stack.

Action: Click on the right-pointing arrow button. You are now at card 13 of the "Soil Venting Stack" stack. Read the text, then enter:
estimated spill mass = 4000 kg
desired remediation time = 180 d
Now click on the "-->Press to Get Rates<--" button

Maximum Removal Rate Estimates

select your unit preference below

☒ [lb/d]

☐ [kg/d]

Note:

These are "maximum removal rates", and should only be used as screening estimates to determine if venting is even feasible at a given site. Continue on to the next card to assess if these rates are acceptable...

Temperature (°C) **18**

Soil Type **Fine Sand**

Soil Permeability Range (darcy) **1** to **10**

Well Radius (in) **2**

Radius of Influence (ft) **40**

Contaminant Type **Weathered Gasoline**

Permeable Zone Thickness (ft) **6.6**

P _w - Well Vacuum (in H ₂ O)	Flowrate Estimates [SCFM] (single well)	Max. Removal Rate Estimates [lb/d] (single well)
5	0.33 to 3.32	6 to 62
10	0.66 to 6.59	12 to 124
20	1.30 to 13.02	25 to 251
40	2.54 to 25.38	52 to 517
60	3.71 to 37.09	80 to 799
120	6.83 to 68.27	178 to 1778
200	10.07 to 100.66	364 to 3636

← 12 →
Print Card

Figure 15. Card 12 of the "Soil Venting Stack" stack.

Is Soil Venting Appropriate?

At this point, you compare the maximum possible removal rate with your desired removal rate.

If the maximum removal rate does not exceed your desired removal rate, then soil venting is not likely to meet your needs, and you should consider another treatment technology, or make your needs more realistic.

In the next cards, we will refine the removal rate estimates, in

Enter ☒ kg ☐ lb

① Estimated Spill Mass **4000**

② Enter Desired Remediation Time **180** days

③ -->Press to get Rates<--

Single Vertical Well Results

Desired Removal Rate:	22.22	[kg/d]
Gauge Vacuum (in H ₂ O):	200	[in H ₂ O]
Min Flowrate @ 200 in H ₂ O	10.07	[SCFM]
Max Flowrate @ 200 in H ₂ O	100.66	[SCFM]
Max. Est. Removal Rate:		
(lower estimate) - per well	164.892	[kg/d]
(upper estimate) - per well	1647.108	[kg/d]

← 13 →

Figure 16. Card 13 of the "Soil Venting Stack" stack.

Result: Your screen should now look like Figure 16. Note that your desired removal rate (=22 kg/d) is less than the estimated maximum removal rates for a single vertical well (=165 to 1650 kg/d). At this point in the screening exercise, therefore, soil venting still appears to be a viable option.

Step 10: **Location:** Card 13 of the "Soil Venting Stack" stack.

Action: Click on the right-pointing arrow button to advance to card 14 of the "Soil Venting Stack" stack. Read the text, then advance to card 15 of the "Soil Venting Stack" by clicking on the right-pointing arrow button. Again, take the time to read the text, then advance to card 16 of the "Soil Venting Stack" stack. The focus of these cards is the prediction of vapor concentrations and removal rates as they change with time due to composition changes. It is important to try to understand the concepts introduced in these cards.

Result: You are at card 16 of the "Soil Venting Stack" stack (see Figure 17).

Step 11: **Location:** Card 16 of the "Soil Venting Stack" stack.

Action: This card is used to finalize your input data prior to calculating vapor concentration and residual soil contamination composition changes with time. Read the instructions in the order that they are numbered. Note that the summary table in the upper right corner of the card contains all the parameter values that you have input thus far. The instructions describe how to change these values, but at this point we will retain the displayed values. Because it is difficult to present the behavior of each compound in a mixture composed of an arbitrary number of compounds, the output is simplified by reporting the behavior in terms of "boiling point" ranges. This simply represents a summation of all compounds whose boiling points fall between pre-specified values. Presented in this fashion, the model results can be interpreted much more quickly. Click on the "tell me more about BP ranges..." button, read the help card, then return to card 16 of the "Soil Venting Stack" stack. Click on the "-->Set Default BP Ranges<--" button. Your screen should now look like Figure 17. Click on the "Generate Predictions" button

Result: The message "Sit Back and Relax..." will appear on your screen, followed by a screen on which the following appears:

"Copyright © Absoft Corp 1988

Copyright © Shell Oil Co 1990

HANG ON ----- YOU WILL BE RETURNED TO HYPERCARD...

OF COMPOUNDS IN LIBRARY = 62"

Then card 17 of the "Soil Venting Stack" stack will appear.

Model Predictions

① To the right is a summary of the data you have input. If you wish to change any of the info, then click on the parameter name, and redo the calculations on the card you will be taken to. Press the blinking 'Return' button to come back

② The model returns output that allows you to determine residual amounts of compounds falling within 5 boiling point ranges. Type in your own ranges, or choose the default values.

Temperature (°C) 18

Soil Type Fine Sand

Soil Permeability Range (darcy) 1 to 10

Well Radius (in) 2

Radius of Influence (ft) 40

Contaminant Type Weathered Gasoline

Permeable Zone Thickness (ft) 6.6

③ --> Set Default BP Ranges <--

Boiling Point Range #1	-50	to	28	C
Boiling Point Range #2	28	to	80	C
Boiling Point Range #3	80	to	111	C
Boiling Point Range #4	111	to	144	C
Boiling Point Range #5	144	to	250	C

④ Generate Predictions

tell me more about BP ranges...
← 16 →
Print Card

Figure 17. Card 16 of the "Soil Venting Stack" stack.

① --> Import Data <--

FIRST PRESS THE IMPORT DATA BUTTON!

These are the results for the contaminant type that you have

Saturated Vapor Concentration at time=0 0.2053E+03 [mg/L]

Min Volume to Remove >90% of Initial Residual 128.48 [L-air/g-residual]

Temperature (°C): 18

Contaminant Type: Weathered Gasoline

QVM(0) L-air/ g-residual	Vapor Conc: [% Initial]	Residual Level [% Initial]	BP #1 Residual [% total]	BP #2 Residual [% total]	BP #3 Residual [% total]	BP #4 Residual [% total]	BP #5 Residual [% total]
.00	100.000	100.000	.690	11.650	24.010	22.140	41.510
.24	75.062	95.000	.123	9.263	23.982	23.000	43.632
.57	58.631	90.022	.000	6.755	23.474	23.820	45.950
.98	48.078	85.034	.000	4.512	22.403	24.577	48.509
1.49	39.390	80.034	.000	2.632	20.771	25.248	51.350
2.11	31.941	75.035	.000	1.222	18.503	25.766	54.509
2.87	25.916	70.035	.000	.385	15.556	26.031	58.028
3.81	21.150	65.037	.000	.068	12.053	25.919	61.959

Launch Excel
← 17 →
Print Card

Figure 18. Card 17 of the "Soil Venting Stack" stack.

▽

19

- Step 12: Location: Card 17 of the "Soil Venting Stack" stack.
 Action: Read the instructions, then click on the "-->Import Data<--" button.
 Result: Your screen should look like Figure 18. The table in the lower part of the card lists model predictions: vapor concentration and residual soil concentration (expressed as a percentage of their initial values), as well as the composition of the residual (expressed as a percentage of the total for each boiling point range) as a function of the amount of air drawn through the contaminated soil. Note that as the volume of air drawn through the soil increases, the vapor concentration and residual soil levels decrease, and the composition of the residual becomes richer in the less volatile compounds (BP Range #5). In the upper right corner of the card are displayed the saturated, or initial, vapor concentration and the minimum amount of air that must be drawn through the soil per gram of initial contaminant to achieve at least a 90% reduction in the initial residual level. This value is used in future calculations as a design parameter.
- Step 13: Location: Card 17 of the "Soil Venting Stack" stack.
 Action: Click on the right-pointing arrow to advance to card 18 of the "Soil Venting Stack" stack.
 Result: You are at card 18 of the "Soil Venting Stack" stack, which should resemble Figure 19. Read the text. A summary of your input parameters appears on the right side of this card. At the bottom appears two calculated values representing the range of the minimum number of wells required to achieve a 90% reduction in the initial residual level in the desired remediation time. These values correspond to idealized conditions, however, they can be used to gauge the efficacy of soil venting at your site. For example, in this case the minimum number of wells ranges between 0.7 - 7, which is not an unreasonable number for a site the size of a service station. If the range had been 100 - 1000, then it might be wise to consider other remediation options.

It is important to recognize that model predictions are intended to serve as guidelines, and are limited in their ability to describe behavior that might be observed at any given site. One should use all the information available, in addition to idealized model predictions to make rational decisions about the applicability of soil venting.

- Step 14: Location: Card 18 of the "Soil Venting Stack" stack.
 Action: Click on the right-pointing arrow button to advance to card 19.
 Result: You are now at card 19 of the "Soil Venting Stack" stack. This card lists several phenomena that can cause one to achieve less than ideal removal rates. Take the time to explore each of these options, then return to card 19 of the "Soil Venting Stack" stack.

Is Venting Appropriate?

This is a complete summary of the data and results. Based upon these numbers, a "minimum number of wells" has been calculated, which should give you some indication of how appropriate venting is for your application. Note that this is the number of wells if circumstances are ideal,

Temperature [°C]:	18
Contaminant Type:	Weathered Gasoline
Soil Type:	Fine Sand
Well Radius [in]:	2
Est. Radius of Influence [ft]:	40
Permeable Zone Thickness [ft]:	6.6
Flowrate per Well (120" Vac) [SCFM]	6.83
Flowrate per Well (120" Vac) [SCFM]	68.27
Min. Vol. of Air [L/g-residual]:	128.48
Estimated Spill Mass:	4000 kg
Desired Remediation Time [days]:	180

0.72

Minimum # of Wells Based on Your Input Parameters

7.23

Figure 19. Card 18 of the "Soil Venting Stack" stack.

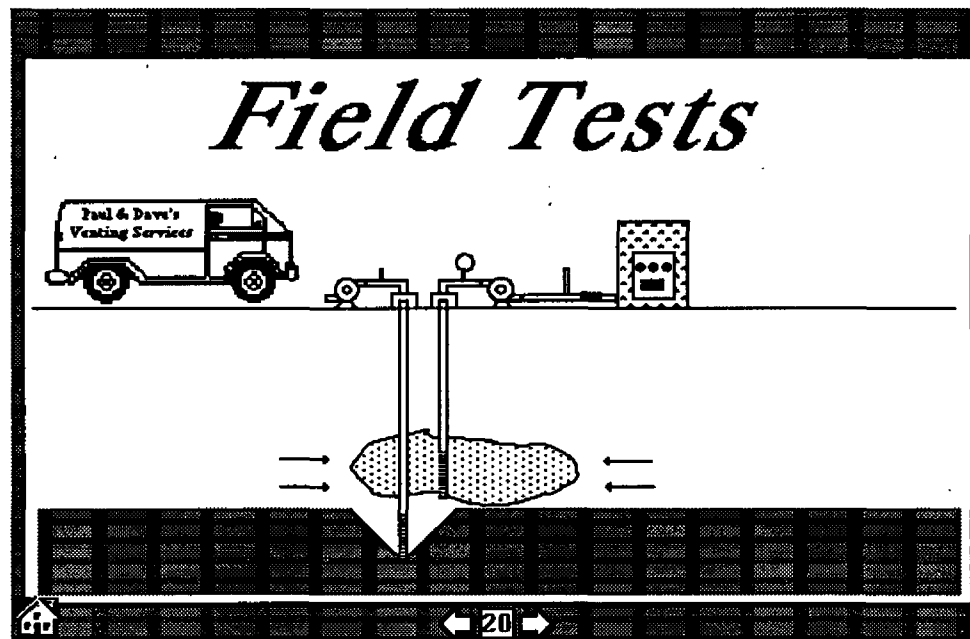


Figure 20. Card 20 of the "Soil Venting Stack" stack.

V.3.3 Sample Problem Exercise - Field Permeability Test.

Note: *It is recommended that you always plot and visually inspect your data prior to attempting to fit it to any theory.*

In this example, we use **HyperVentilate** to analyze air permeability test data from the site pictured in Figure 10. We will focus on results from the lower fine to medium sand zone (45 - 50 ft below ground surface). Advance to card 20 (Figure 20) of the "Soil Venting Stack" stack to begin.

- Step 1: Location: Card 20 of the "Soil Venting Stack" stack.
 Action: Using the right-pointing arrow, advance to card 21 of the "Soil Venting Stack" stack. Read the text, then click on the "Air Permeability Test" button.
 Result: You are at card AP1 of the "Air Permeability Test" stack.
- Step 2: Location: Card AP1 of the "Air Permeability Test" stack
 Action: Read the instructions, then click on the "Show Me Set-up" button. Take a look at the figure, then click the "Return" button to return to card AP1 of the "Air Permeability Test" stack. Now click on the "Test Instructions" button.
 Result: You are at card AP3 of the "Air Permeability Test" stack.
- Step 3: Location: Card AP3 of the "Air Permeability Test" stack.

Action: Read the text, look at the sample data (click on the "show me sample data" button) then enter the following values for this example:

soil layer thickness = 6.6 ft
estimated radius of influence = 50 ft
air permeability test flowrate = 15 CFM

Click on the "-->Calculate<--" button to estimate how long the air permeability test should be conducted.

Result: Your results should match those displayed below in Figure 21.

Step 4: Location: Card AP3 of the "Air Permeability Test" stack.

Action: Click on the "Return" button to return to card AP1 of the "Air Permeability Test" stack. Then click on the "Data Analysis" button.

Result: You are now at card AP5 of the "Air Permeability Test" stack.

Step 5: Location: Card AP5 of the "Air Permeability Test" stack.

Action: Read the text, then step through cards AP6 and AP7, until you reach card AP8 of the "Air Permeability Test" stack.

Result: You are now at card AP8 of the "Air Permeability Test" stack.

Air Permeability Test - Instructions

1)
Identify soil zones to be treated

2)
Install vapor extraction well(s) in this zone(s). Existing monitoring wells may be used, when the screen interval extends only into the zone to be treated. Note the extraction well radius and borehole size. Insure that the well is not "connected" to other soil zones through the borehole (use cement/grout to seal annular borehole region).

show me sample data

Pore Volume Estimation:

Enter.

1) Soil Layer Thickness [ft]: 6.6

2) Estimated Radius of Influence [ft]: 50

3) Air Perm. Test Flowrate [CFM]: 15

--> Calculate <--

Pore Volume: 15543 ft**3

Time to Extract a Pore Volume: 0.72 days

Return AP3

Figure 21. Card AP3 of the "Air Permeability Test" stack.

r = 53 ft		r = 32.4 ft	
Time [min]	Gauge Vacuum [in H ₂ O]	Time [min]	Gauge Vacuum [in H ₂ O]
9	0.1	4	1.2
11	0.2	7	3.0
15	0.2	9	4.3
23	0.4	12	5.5
30	0.7	16	6.9
40	1.3	24	9.9
100	2.8	30	11
		39	13
		52	16
		77	20
		99	21
		110	23
		121	24.5
		141	25.5

While entering the data it is convenient to place the cursor in the time column, type in the time value, then use the "tab" key to advance to the vacuum reading column. Enter the corresponding vacuum value, then hit the "tab" key again. As you see, this advances the cursor to the time column again. Now click the "-->Calculate<--" button.

Result: Your results should match those displayed in Figure 22. Soil permeability values have been calculated by fitting the field data to the theoretical model described in cards AP5 - AP7 of the "Air Permeability Test" stack.

Step 7: **Location:** Card AP8 of the "Air Permeability Test" stack.
 Action: Review the results, then click on the "Explanation & Statistics" button. This advances you to card AP9 of the "Air Permeability Test" stack, which lists correlation coefficients for the data fitting process. These values give an indication of how well the model describes the behavior observed in the field. Values approaching unity indicate a good fit. Your results should match those given in Figure 23.

Air Permeability Test - Data Analysis (cont.)

① Enter radial distances of monitoring points → r= (ft)

② Enter measured times and gauge vacuums →

③ Enter (optional):

a) flowrate (SCFM)

b) screened interval thickness (ft)

→ Calculate ←

r= <input type="text" value="53"/> (ft)		r= <input type="text" value="32.4"/> (ft)		r= <input type="text"/> (ft)	
(min)	(in H2O)	(min)	(in H2O)	(min)	(in H2O)
9	0.1	4	1.2		
11	0.2	7	3		
15	0.2	9	4.3		
23	0.4	12	5.5		
30	0.7	16	6.9		
40	1.3	24	9.9		
100	2.8	30	11		
		39	13		
		52	16		
		77	20		

clear
clear
clear

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

k= darcy (A)

k= darcy (B)

Return
Explanation & Statistics
AP8

Figure 22. Card AP8 of the "Air Permeability Test" stack.

Air Permeability Test - Data Analysis (cont.)

On the previous Card (AP8), the data you input were fit to the approximate expression given on Card AP6. It was analyzed using both methods described on card AP7, if you input values for the extraction well flowrate (Q) and the stratum thickness (m). Below each column of data, the two calculated permeability values are denoted by:

darcy(A) - refers to calculation method 1 (see Card AP7)
darcy(B) - refers to calculation method 2 (see Card AP7)

During the regression analyses, the data expressed as pairs of points (ln(t), P') are fit to a line. The "correlation coefficient", r, is a measure of how well the data conform to the theoretical curve. As r→1, the data points all fall on the theoretical curve. At the right are given the correlation coefficient values for the three data sets. For more info on the meaning of r, consult any introductory Statistics book.

Correlation Coef.
(r)

data set #1:

data set #2:

data set #3:

Return
AP9

Figure 23. Card AP9 of the "Air Permeability Test" stack.

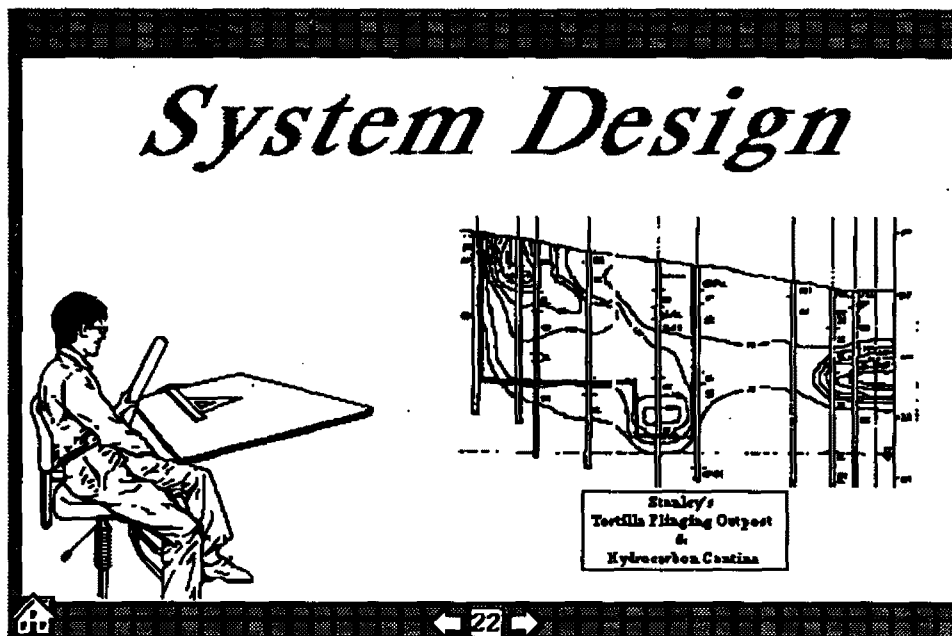


Figure 24. Card 22 of the "Soil Venting Stack" stack.

V.3.4 Sample Problem Exercise - System Design

In this example we illustrate the use of HyperVentilate for system design guidance. As in §V.3.2 and §V.3.3, we use the sample site presented in Figure 10. At this site gasoline was detected in three distinct soil strata: a fine to coarse zone located 10 - 30 ft below ground surface (BGS), a silty clay/clayey silt zone located 30 to 42 ft BGS, and a fine to medium sand zone that extends from 42 ft BGS to the deepest soil boring (60 ft BGS). Groundwater is detected in monitoring wells at about 50 ft BGS.

Advance to card 22 of the "Soil Venting Stack" stack to begin (Figure 24).

- Step 1: Location: Card 22 of the "Soil Venting Stack" stack.
 Action: Use the right-pointing arrow to advance to card 23 of the "Soil Venting Stack" stack. Read the text, then advance to card 24 of the "Soil Venting Stack" stack.
 Result: Card 24 of the "Soil Venting Stack" stack, which appears in Figure 25, should be displayed.
- Step 2: Location: Card 24 of the "Soil Venting Stack" stack.
 Action: Read the text, explore using some of the options. You will find that the options: "Well Location", "Well Construction", "Surface Seals", "Groundwater Pumping System", and "Vapor Treatment" provide some useful guidance information on aspects and components of a soil venting system. Return to card 24.
 Result: Card 24 of the "Soil Venting Stack" stack should be displayed.

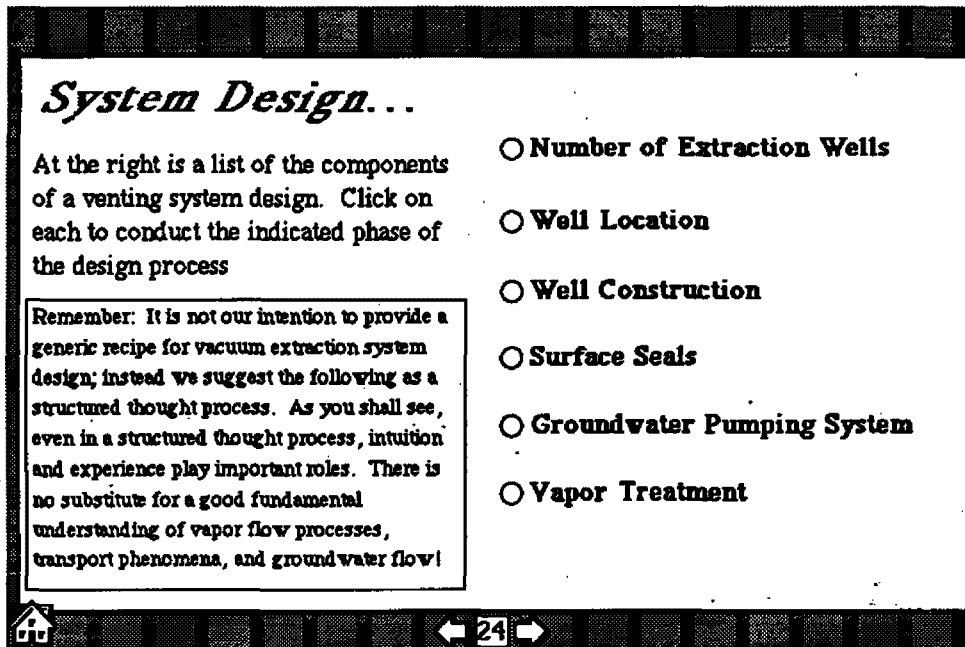


Figure 25. Card 24 of the "Soil Venting Stack" stack.

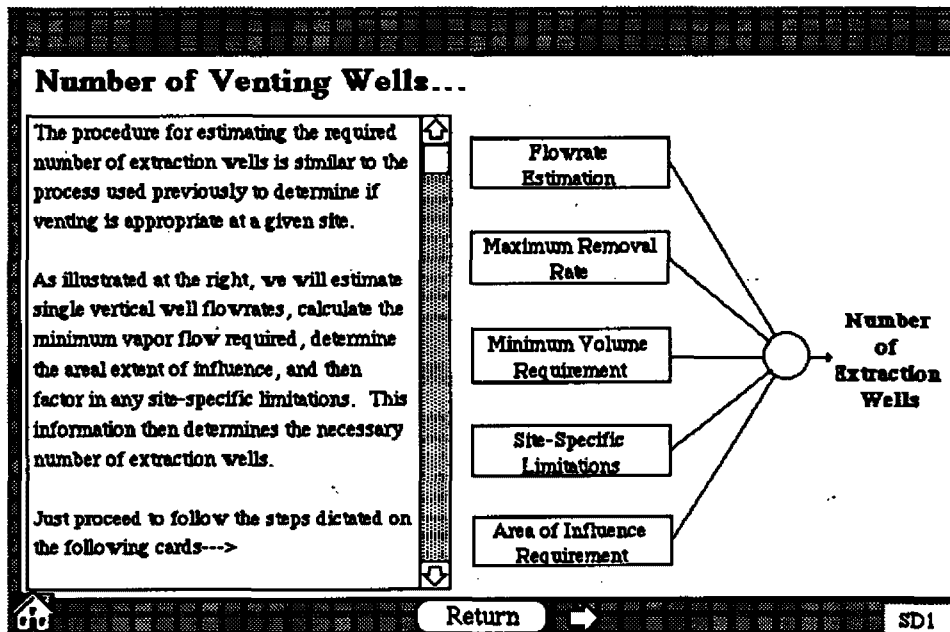


Figure 26. Card SD1 of the "System Design" stack.

- Step 3: Location: Card 24 of the "Soil Venting Stack" stack.
 Action: Select "Number of Extraction Wells" from the list of options.
 Result: Card SD1 of the "System Design" stack should be displayed, as pictured in Figure 26.
- Step 4: Location: Card SD1 of the "System Design" stack.
 Action: Read the text, then use the right-pointing arrow to advance to card SD2.
 Result: Card SD2 of the "System Design" stack should be displayed.
- Step 5: Location: Card SD2 of the "System Design" stack.
 Action: Read the instructions on the card, enter the following values into the table, then click on the "Update" button:

<i>Parameter</i>	<i>Soil Zone</i>		
	<i>Medium Sand</i>	<i>Clayey Silt</i>	<i>Fine Sand</i>
subsurface interval (ft BGS)	10 - 30	30 - 43	43 - 50
description of contaminant	gasoline	gasoline	gasoline
radial extent of contamination (ft)	20	20	20
interval thickness (ft)	20	13	7
average contaminant concentration	100	1000	10000

Result: Card SD2 should now resemble Figure 27.

- Step 6: Location: Card SD2 of the "System Design" stack.
 Action: Use the right-pointing arrow to advance to card SD3 of the "System Design" stack.
 Result: Card SD3 of the "System Design" stack should be displayed.
- Step 7: Location: Card SD3 of the "System Design" stack.
 Action: Read the text. Note that "clicking" on many of the table headings will take you to "help" cards. Take a few minutes to explore the use of these, then enter the following information:

<i>Parameter</i>	<i>Soil Zone</i>		
	<i>Medium Sand</i>	<i>Clayey Silt</i>	<i>Fine Sand</i>
permeability (darcy)	10 - 100	0.01 - 0.1	1 - 10
design vacuum (in H ₂ O)	40	40	40
Well Construction:			
Radius of Influence (ft)	40	40	40
Extraction Well Radius (in)	2	2	2
Extraction Well Screen Thickness (ft)	10	5	5

Design Input Parameters...

(soil stratigraphy & contaminant characteristics)

Please enter the required information for each distinct soil layer, click on the "Update" button, and then proceed to the next card (i.e. click on right arrow at bottom).
(the tab key can be used to move between cells)

Select the total mass units that you prefer
☒ [kg]
☐ [lb]

Clear All Entries

Description of Soil Unit	Depth BGS* [ft]		Description of Contamination	Contaminant Distribution			Calc. Total Mass [kg]
				radius [ft]	interval thickness [ft]	average conc. [mg/kg]	
1 Medium Sand	10	to 30	gasoline	20	20	100	120.9
2 Clayey Silt	30	to 43	gasoline	20	13	1000	786.0
3 Fine Sand	43	to 50	gasoline	20	7	10000	4232.3
4		to					0.0
5		to					0.0
6		to					0.0
7		to					0.0
8		to					0.0

* Below Ground Surface

Update

Return

SD2

Figure 27. Card SD2 of the "System Design" stack.

Design Input Parameters...

Please enter the required information for each distinct soil layer, and then proceed to the next card.

Note: - click on any table heading to get more info
 - use tab key to move between cells

☐ Medium Sand
☐ Fine Sand
☐ Silty Sand
☐ Clayey Silts

Description of Soil Unit	Permeability* [darcy]		Design Vacuum (in H2O)	Extraction Well Construction			Critical Volume of Air** [L/g]	Efficiency (%)
				well radius [in]	screen thickness [ft]	radius of influence [ft]		
1 Medium Sand	10	to 100	40	2	10	40	128.48	100
2 Clayey Silt	0.01	to 1	40	2	5	40	128	100
3 Fine Sand	1	to 10	40	2	5	40	128	100
4		to						
5		to						
6		to						
7		to						
8		to						

* Enter or choose from list at top right ** minimum volume of vapor required to achieve remediation

Clear All Entries
Return

SD3

Figure 28. Card SD3 of the "System Design" stack.

The "Critical Volume of Air" is calculated by the same procedure used previously in §V.3.2 (steps 10 -13). To initiate this calculation, "click" on the "Critical Volume of Air**" heading.

Result: Card SD5 of the "System Design" stack appears on your screen (Figure 29).

Step 8: **Location:** Card SD5 of the "System Design" stack.

Action: Read the text carefully. The focus of this card is the prediction of vapor concentrations and removal rates as they change with time due to composition changes. It is important to try to understand the concepts introduced in this card. For more information, read the reference article contained in the appendix. Click on the "Do a Calculation" button to advance to card SD6 of the "System Design" stack (Figure 30).

Result: Card SD6 of the "System Design" stack appears on your screen.

Step 9: **Location:** Card SD6 of the "System Design" stack.

Action: This card is used to finalize your input data prior to calculating vapor concentration and residual soil contamination composition changes with time. Read the instructions in the order that they are numbered, then enter "18" for the temperature and select "weathered gasoline" from the three composition options. Because it is difficult to present the behavior of each compound in a mixture composed of an arbitrary number of compounds, the output is simplified by reporting the behavior in terms of "boiling point" ranges. This simply represents a summation of all compounds whose boiling points fall between pre-specified values. Presented in this fashion, the model results can be interpreted much more quickly. Click on the "tell me more about BP ranges..." button, read the help card, then return to card SD6 of the "System Design" stack. Click on the "-->Set Default BP Ranges<--" button. Your screen should now look like Figure 30. Click on the "Generate Predictions" button

Result: The message "Sit Back and Relax..." will appear on your screen, followed by a screen on which the following appears:

"Copyright © Absoft Corp 1988

Copyright © Shell Oil Co 1990

HANG ON ----- YOU WILL BE RETURNED TO HYPERCARD...

OF COMPOUNDS IN LIBRARY = 62"

Then card SD7 of the "System Design" stack will appear as shown in Figure 31.

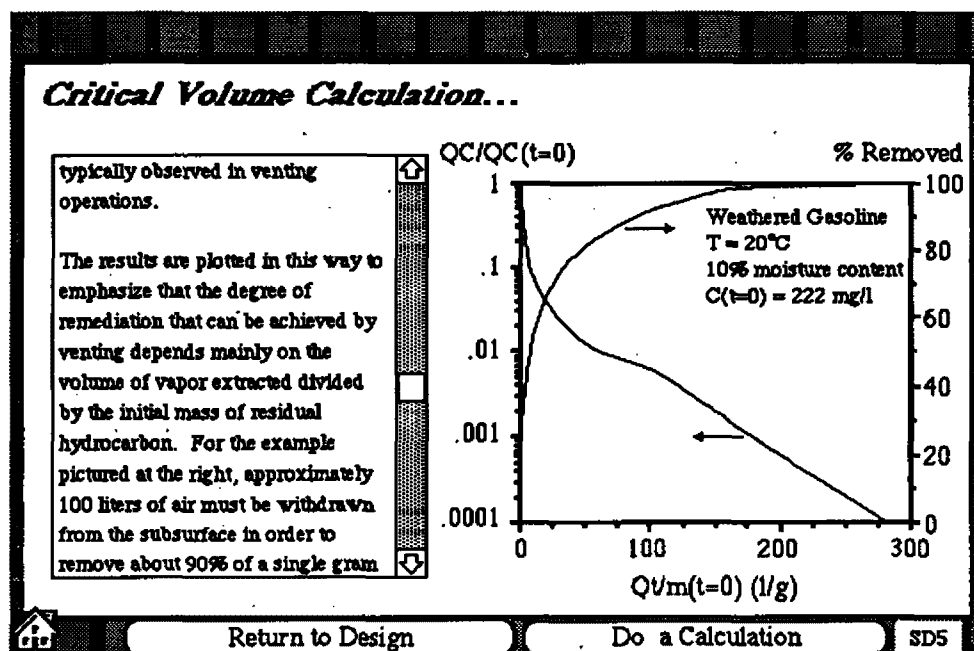


Figure 29. Card SD5 of the "System Design" stack.

Critical Volume Predictions...

Simply enter the temperature at the right, and then specify the composition of your contaminant. If you are unsure about this, click on the "About Composition..." button located at the lower right.

The model returns output that allows you to determine residual amounts of compounds falling within 5 boiling point ranges. Type in your own ranges, or choose the default values.

① Temperature (°C)

② Contaminant Composition (choose one)

- ☐ Enter Distribution
- ☐ "Fresh" Gasoline
- ☒ "Weathered" Gasoline

③ --> Set Default BP Ranges <--

Boiling Point Range #1	-50	to	28	C
Boiling Point Range #2	28	to	80	C
Boiling Point Range #3	80	to	111	C
Boiling Point Range #4	111	to	144	C
Boiling Point Range #5	144	to	250	C

④

Figure 30. Card SD6 of the "System Design" stack.

- Step 10: Location: Card SD7 of the "System Design" stack.
 Action: Read the instructions, then click on the "-->Import Data<--" button.
 Result: Your screen should look like Figure 31. The table in the lower part of the card lists model predictions: vapor concentration and residual soil concentration (expressed as a percentage of their initial values), as well as the composition of the residual (expressed as a percentage of the total for each boiling point range) as a function of the amount of air drawn through the contaminated soil. Note that as the volume of air drawn through the soil increases, the vapor concentration and residual soil levels decrease, and the composition of the residual becomes richer in the less volatile compounds (BP Range #5). In the upper right corner of the card are displayed the saturated, or initial, vapor concentration and the minimum amount of air that must be drawn through the soil per gram of initial contaminant to achieve at least a 90% reduction in the initial residual level. This value is used in future calculations as a design parameter.
- Step 11: Location: Card SD7 of the "System Design" stack.
 Action: Click on the "Return to System Design" button
 Result: A dialog box will appear asking: "Transfer Critical Volume Value?". Click on the "Yes" button. You will now be prompted by another dialog box asking: "What soil unit # is this value for?". Enter "1" into the appropriate place then click on the "OK" button. You will now be transferred back to card SD3 of the "System Design" stack. Note that the value "128.48" has been entered into the "Critical Volume of Air**" column for the medium sand soil unit.
- Step 12: Location: Card SD3 of the "System Design" stack.
 Action: Enter "128" into the "Critical Volume of Air**" column for the clayey silt and fine sand soil units. For this example problem enter "100" for the efficiency in all three soil units
 Result: Card SD3 should now resemble Figure 28.
- Step 13: Location: Card SD3 of the "System Design" stack.
 Action: Click on the right-pointing arrow at the bottom of the page to advance to Card SD4 of the "System Design" stack.
 Result: Card SD4 of the "System Design" stack should appear on your screen.
- Step 14: Location: Card SD4 of the "System Design" stack.
 Action: Assume that you wish to remediate this site in 180 days. Enter "180" in the "Time for Clean-up" column for each soil unit. Click on the "Update" button.
 Result: HyperVentilate calculates a range of flowrates to a single vertical well, then uses this value and other input parameters to determine the minimum number of wells required based on two approaches.

To read about these, click on the "Number of Wells" column heading. Your card SD4 should resemble Figure 32.

It is important to recognize that model predictions are intended to serve as guidelines, and are limited in their ability to describe behavior that might be observed at any given site. One should use all the information available, in addition to idealized model predictions to make rational decisions about the applicability of soil venting.

You can read about the effect of venting at this site in the article: "Soil Venting at a California Site: Field Data Reconciled with Theory", by P. C. Johnson, C. C. Stanley, D. L. Byers, D. A. Benson, and M. A. Acton, in *Hydrocarbon Contaminated Soils and Groundwater: Analysis, Fate, Environmental Health Effects, and Remediation Volume 1*, P. T. Kostecki and E. J. Calabrese, editors, Lewis Publishers, p.253 - 281, 1991.

① --> Import Data <--

FIRST PRESS THE IMPORT DATA BUTTON!

These are the results for the contaminant type that you have

Saturated Vapor Concentration at time=0: **0.2053E+03** [mg/L]

Min Volume to Remove >90% of Initial Residual: **128.48** [L-air/g-residual]

Temperature (°C): **18**

Contaminant Type: **Weathered Gasoline**

Q/M(0) L-air/ g-residual	Vapor Conc. [% Initial]	Residual Level [% Initial]	BP #1 Residual [% total]	BP #2 Residual [% total]	BP #3 Residual [% total]	BP #4 Residual [% total]	BP #5 Residual [% total]
.00	100.000	100.000	.690	11.650	24.010	22.140	41.510
.24	75.062	95.000	.123	9.263	23.982	23.000	43.632
.57	58.631	90.022	.000	6.755	23.474	23.820	45.950
.98	48.078	85.034	.000	4.512	22.403	24.577	48.509
1.49	39.390	80.034	.000	2.632	20.771	25.248	51.350
2.11	31.941	75.035	.000	1.222	18.503	25.766	54.509
2.87	25.916	70.035	.000	.385	15.556	26.031	58.028
3.81	21.150	65.037	.000	.068	12.053	25.919	61.959

Launch Excel
Return to System Design
Print Card
SD7

Figure 31. Card SD7 of the "System Design" stack.

Design Input Parameters...

Please enter (1) the desired time period for remediation, (2) the design gauge vacuum, and then (3) click the "update" button.

Note: - click on any table heading to get more info
- use tab key to move between cells

③ Update

	Description of Soil Unit	① Time for Clean-up [days]	② Design Vacuum (in H2O)	Flowrate per Vapor Extraction Well [SCFM]		Minimum Number of Wells				
						Based on Area	Based on Critical Volume**			
1	Medium Sand	180	40	38.4	to	384.4	0.2	0.0	to	0.0
2	Clayey Silt	180	40	0.0	to	0.2	0.2	64.3	to	643.0
3	Fine Sand	180	40	1.9	to	19.2	0.2	3.5	to	34.6
4				NA	to	NA	NA	NA	to	NA
5				NA	to	NA	NA	NA	to	NA
6				NA	to	NA	NA	NA	to	NA
7				NA	to	NA	NA	NA	to	NA
8				NA	to	NA	NA	NA	to	NA

NA - not enough input data

** minimum volume of vapor required to achieve remediation

Clear All Entries
Return
SD4

Figure 32. Card SD4 of the "System Design" stack.

References

Hutzler, N. J., Murphy, B. E., and Gierke, J. S., State of Technology Review: Soil Vapor Extraction Systems, U.S.E.P.A, EPA/600/2-89/024, June 1989.

Johnson, P. C., Kemblowski, M. W., and Colthart, J. D., Practical Screening Models for Soil Venting Applications, NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, TX, 1988.

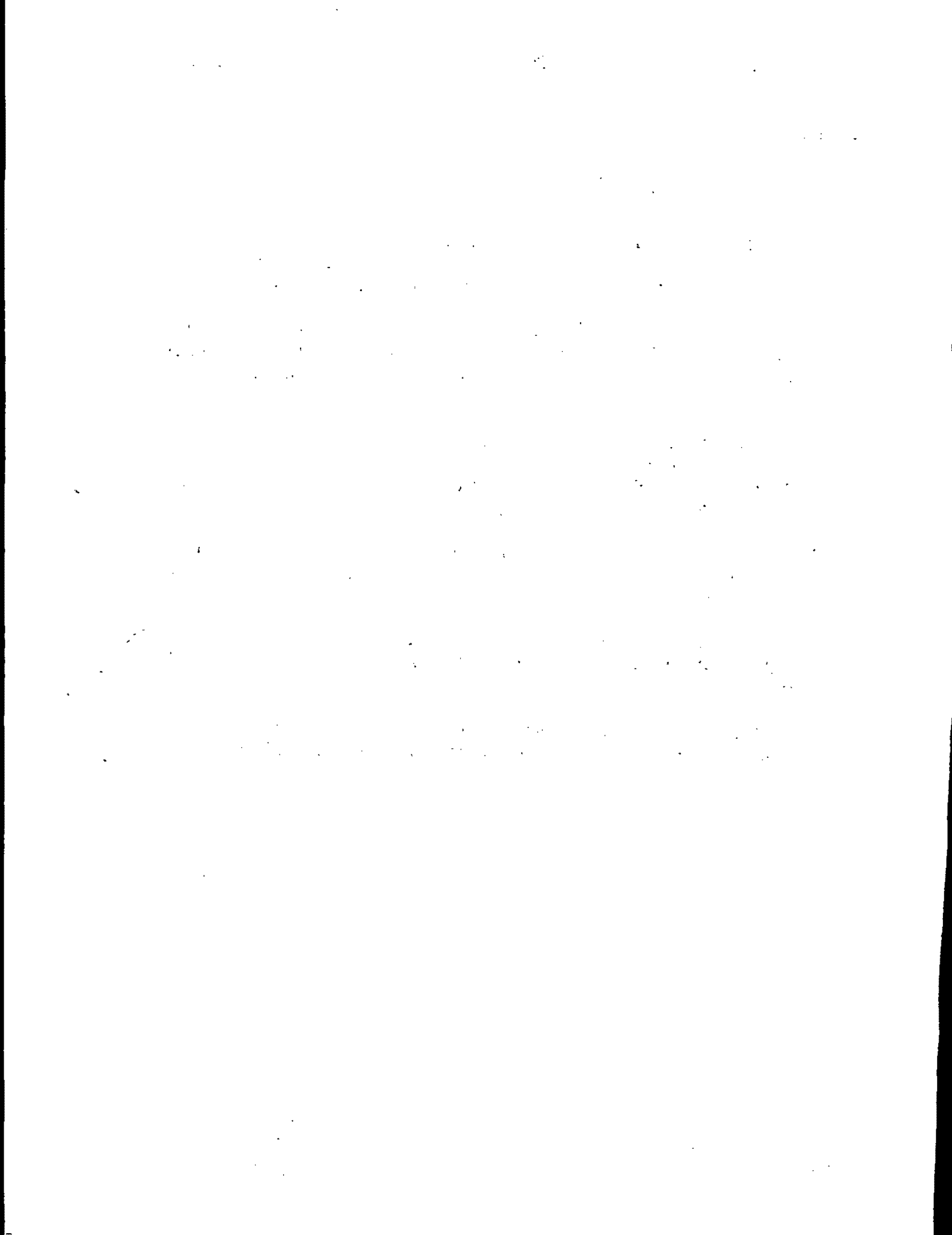
Johnson, P. C., Stanley, C. C., Kemblowski, M., W., Byers, D. L., and Colthart, J. D., A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems, to appear in Ground Water Monitoring Review, Spring 1990.

Marley, M. C., and Hoag, G. E., Induced Soil Venting for the Recovery/Restoration of Gasoline Hydrocarbons in the Vadose Zone, NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, TX, 1984.

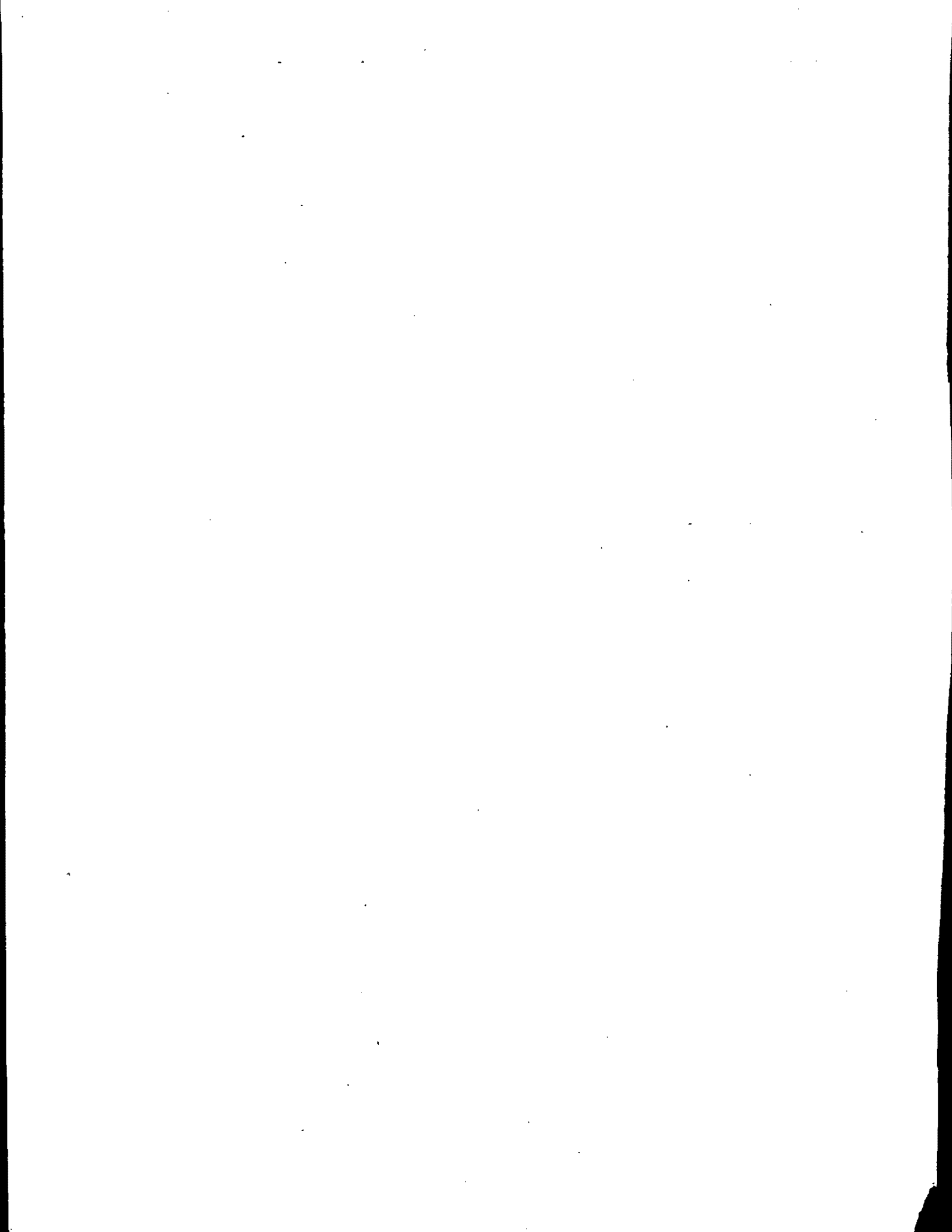
Marley, M. C., Baehr, A. L., and Hult, M. F., Evaluation of Air-Permeability in the Unsaturated Zone using Pneumatic Pump Tests: 1. Theoretical Considerations, in review, 1990.

Thornton, J. S. and Wootan, W. L., Venting for the Removal of Hydrocarbon Vapors from Gasoline Contaminated Soil, J. Environ. Sci. Health, A17(1), 31-44, 1982.

Newell, C. J., Haasbeek, J. F., and Bedient, P. B., OASIS: A Graphical Decision Support System for Ground-Water Contaminant Modeling, Ground Water, 28 (2), 224 - 234, March - April 1990.



Appendix A: "Soil Venting Stack" stack cards.



This Copy Relays to: **Dr. Paul**

A Practical Approach to the Design, Operation, and Monitoring of In-Situ Soil Venting Systems

version 1.01
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Shell Oil Company

A HyperCard Stack Created by:
Paul C. Johnson, Ph.D.
Amy J. Stubbins
Shell Development
Worthington Research Center

Economics
System Monitoring
Field Test
Site Investigation
About Soil Venting

System Shut-Down
System Design
Is Venting Feasible?
The "Practical Approach"

Buttons:
About This Stack
Go to First Card

This HyperCard Stack was created to help guide environmental scientists through the thought process necessary to decide if and how soil venting might be applied to remediate a given site. The organization and logic of this stack follows the paper:

"A Practical Approach to the Design, Operation, and Monitoring of In-Situ Soil Venting Systems"

by:
P. C. Johnson, C. C. Stanley, M. W. Kamblewski, J. D. Colburt, & D. L. Byers

published in *Ground Water Monitoring Review*, Spring 1990, p. 159-178

If at this point you do not feel comfortable with the use of the buttons, please click once on "I" for more info on the mechanics of this stack...

About Soil Venting ...

Soil Venting (a.k.a. "in-situ soil venting", "vacuum extraction", & "in-situ vapor extraction") is rapidly becoming one of the most practiced soil remediation processes for permeable soils contaminated with relatively volatile hydrocarbons.

The underlying phenomena that influence the success of any soil venting operation are easily understood. By applying a vacuum

Buttons:
2

In-Situ Soil Venting System Design Process

You can click on any block in this diagram to get more information about that particular step. Or you can begin at the start of the process by clicking on either the "Leak or Spill Discovered" box, or the right-directed arrow at the bottom of this card.

Buttons:
3
Print Flow Diagram

Leak or Spill Discovered...

In the following cards we will assume that a leak or spill has been discovered, and the appropriate emergency response and abatement have taken place.

Now we will step through a logical thought process to decide if soil venting is appropriate at this site. The previous card displays the flowchart that is the basis for the thought process. Clicking within any process box will take you to that section of the stack dealing with that aspect of the thought process.

Buttons:
4

Preliminary Site Investigation

Whenever a soil contamination problem is detected or suspected, a site investigation is conducted to characterize and delineate the zone of soil and groundwater contamination. In general, the site characterization is conducted in two stages. The emergency response and abatement phase assesses the immediate impact on potential human and environmental receptors, and is conducted in a relatively short period of time (days). A detailed site characterization then follows. Its purpose, like the emergency response and abatement phase, is to determine potential migration pathways and assess the environmental impact associated with present

Buttons:
5
Print Text
Text Summary

Screen Treatment Alternatives

With any contaminated site, one should explore the feasibility of all treatment processes. After compiling a list of alternatives, selection criteria (cost, speed, permitting problems) should be established, and then the final choice(s) made.

Soil Venting is most likely to be successful when soils are sandy and the contaminant is volatile.

Other options are available, however,

- ☐ Thermal Desorption
- ☐ Incineration
- ☐ Composting
- ☐ Land Farming
- ☐ In-Situ Biostimulation
- ☐ Solidification/Stabilization
- ☐ Solvent Extraction/Soil Washing

Decision Matrix

Buttons:
6

Is Venting Appropriate?

Read This

At this point we will proceed through a simple thought process to decide if soil venting is a feasible alternative. As mentioned earlier, the three main factors that govern the success of a venting operation are:

- vapor flowrate
- vapor concentrations
- subsurface stratigraphy (or the location of contaminants relative to the vapor flowpath)

Buttons:
7

Flowrate Estimation:

- ☐ Medium Sand
- ☒ Fine Sand
- ☐ Silty Sand
- ☐ Clayey Silt
- ☐ Input Your Own Permeability Range

Permeability Range
[] to []

Well Radius: 2 in
Radius of Influence: 40 ft
Interval Thickness*: 6.6 ft

→ Calculate Flowrate Ranges ←

* thickness of screened interval, or permeable zone (whichever is smaller).

- 1) Choose Soil Type, or Optional - Enter your own permeability values (Assy)
- 2) Enter Well Radius (in)
- 3) Enter Radius of Influence (ft) & Interval Thickness*
- 4) Optional - Enter your own well vacuum (405" = max)
- 5) Click button to calculate Predicted Flowrate Ranges

Predicted Flowrate Ranges

Well Vacuum P_w (in H ₂ O)	Flowrate (SCFM) (single well)
5	0.33 to 3.32
10	0.66 to 6.59
20	1.30 to 13.02
40	2.54 to 25.38
60	3.71 to 37.09
120	6.83 to 68.27
200	10.07 to 100.66

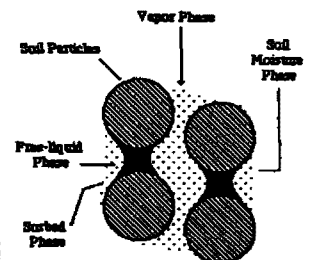
About Soils & Unit Conversions

Info about Calculation

Vapor Concentration Estimation:

The maximum achievable removal rate occurs whenever the vapors removed by venting are "saturated" or in equilibrium with the contaminant/soil matrix.

In the next card you will estimate the maximum vapor concentration of your contaminant. Just follow the instructions in the upper left corner of the next card.



Vapor Concentration Estimation - Calculation

- 1) Type in Temperature (°C) (hit <return>) 20
- Click to Enter Composition of Contaminant or Choose one of the Default Distributions
- 2) Enter Distribution ☐ "Fresh" Gasoline ☒ "Weathered" Gasoline
- 3) Click to View Distributions, (optional) View Distributions
- 4) Click to Perform Calculations Perform Calculations

Results

Sum of Mass Fractions
Calc. Vapor Pressure [] atm
Calc. Vapor Concentration [] mg/l

How Do I Measure a Distribution?

About Calculation

Print Card

Removal Rate Estimates

The maximum achievable removal rate occurs whenever the vapors removed by venting are "saturated" or in equilibrium with the contaminant/soil matrix.

The "Removal Rate" is simply the product of the flowrate times the vapor concentration. The values you input on Cards 8 & 10 will be used to generate removal rate estimates.

Maximum Removal Rate = Maximum Vapor Concentration x Estimated Vapor Flowrate

We calculate this "maximum" removal rate to determine if, even under the best conditions (estimated vapors & no composition changes w/time), venting can meet your needs.

Click on the button below to generate these values...

Calculate Estimates

Maximum Removal Rate Estimates

Select your unit preference below

- ☒ [lb/d]
- ☐ [kg/d]

Note:

These are "maximum removal rates", and should only be used as screening estimates to determine if venting is even feasible at a given site. Continue on to the next card to assess if these rates are acceptable...

Temperature (°C) 18
Soil Type Fine Sand
Soil Permeability Range (Assy) 1 to 10
Well Radius (in) 2
Radius of Influence (ft) 40
Contaminant Type Weathered Gasoline
Permeable Zone Thickness (ft) 6.6

P_w - Well Vacuum (in H ₂ O)	Flowrate Estimate (SCFM) (single well)	Max. Removal Rate Estimate (lb/d) (single well)
5	0.33 to 3.32	6 to 62
10	0.66 to 6.59	12 to 124
20	1.30 to 13.02	25 to 251
40	2.54 to 25.38	52 to 517
60	3.71 to 37.09	80 to 799
120	6.83 to 68.27	178 to 1778
200	10.07 to 100.66	354 to 3636

Print Card

Is Soil Venting Appropriate?

At this point, you compare the maximum possible removal rate with your desired removal rate.

If the maximum removal rate does not exceed your desired removal rate, then soil venting is not likely to meet your needs, and you should consider another treatment technology, or make your needs more realistic.

In the next cards, we will refine

- 1) Enter Estimated Spill Mass 4000 @ kg
- 2) Enter Desired Remediation Time 180 days
- 3) → Press to get Results ←

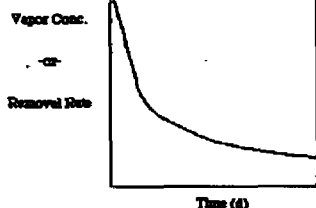
Single Vertical Well Results

Desired Removal Rate: 22.2 [lb/d]
Gauge Vacuum (in H₂O): 200 [in H₂O]
Min Flowrate @ 200 in H₂O: 10.07 [SCFM]
Max Flowrate @ 200 in H₂O: 100.66 [SCFM]
Max. Est. Removal Rate:
(lower estimate) - per well: 164.892 [lb/d]
(upper estimate) - per well: 1647.108 [lb/d]

Is Soil Venting Appropriate? - Refined Estimates

The preceding estimates are useful only as a "first cut", and should be refined if venting is still a potentially feasible option.

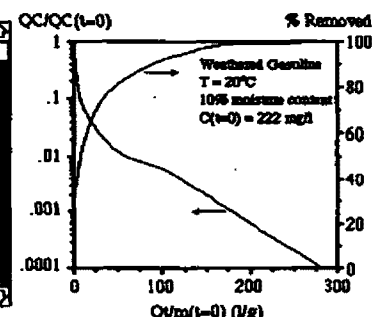
Typically during soil venting, the measured vapor concentration and removal rate dependence on time resembles the plot on the right (when the total vapor flowrate is relatively constant).



More Detailed Calculations

Pictured at the right are the results of sample model predictions, for a weathered gasoline sample.

The vertical axis represents either normalized concentrations $[C(t)/C(t=0)]$, or normalized removal rates $[QC(t)/QC(t=0)]$, while the horizontal axis represents the total volume of vapor



Model Predictions

① To the right is a summary of the data you have input. If you wish to change any of the info, then click on the parameter name, and redo the calculations on the card you will be taken to. Press the blinking "Return" button to come back.

② The model means output that allows you to determine residual amounts of compounds falling within 5 boiling point ranges. Type in your own ranges, or choose the default values.

③ --> Set Default BP Ranges <--

Boiling Point Range #1	-50	to	28	C
Boiling Point Range #2	28	to	80	C
Boiling Point Range #3	80	to	111	C
Boiling Point Range #4	111	to	144	C
Boiling Point Range #5	144	to	250	C

④ Generate Predictions

⑤ --> Import Data <--

⑥ --> Launch Excel <--

⑦ --> Print Card <--

① --> Import Data <--

② --> Launch Excel <--

③ --> Print Card <--

④ --> Set Default BP Ranges <--

⑤ --> Generate Predictions <--

⑥ --> Launch Excel <--

⑦ --> Print Card <--

Is Venting Appropriate?

This is a complete summary of the data and results. Based upon these numbers, a "minimum number of wells" has been calculated, which should give you some indication of how appropriate venting is for your application. Note that this is the number of wells if circumstances are ideal.

① --> Launch Excel <--

② --> Print Card <--

③ --> Set Default BP Ranges <--

④ --> Generate Predictions <--

⑤ --> Launch Excel <--

⑥ --> Print Card <--

Other Considerations

The subsurface is difficult to characterize, and usually conforms to our notion of a "sand box". There are three general classes of situations that will cause venting removal rates to be less than those predicted for the ideal case. Each of these are discussed in "A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems". You can learn more about each by clicking on the buttons to the right.

In addition, when contaminants are located close to ground water, the effect of the vacuum on the water table level can significantly impact a venting system's performance. To learn about this, click on the "Ground Water Upwelling" button.

① --> Launch Excel <--

② --> Print Card <--

③ --> Set Default BP Ranges <--

④ --> Generate Predictions <--

⑤ --> Launch Excel <--

⑥ --> Print Card <--

Field Tests

① --> Launch Excel <--

② --> Print Card <--

③ --> Set Default BP Ranges <--

④ --> Generate Predictions <--

⑤ --> Launch Excel <--

⑥ --> Print Card <--

Field Tests

Prior to the design of an in situ soil venting system, it is desirable to obtain more refined estimates of the unsaturated zone permeability, potential vapor flow rates, and contaminant vapor concentrations. In addition, if a groundwater pumping system might be installed, then aquifer characteristics must also be determined.

Click on the buttons to the right to learn about these tests, or to analyze data that you have already collected.

① --> Launch Excel <--

② --> Print Card <--

③ --> Set Default BP Ranges <--

④ --> Generate Predictions <--

⑤ --> Launch Excel <--

⑥ --> Print Card <--

System Design

① --> Launch Excel <--

② --> Print Card <--

③ --> Set Default BP Ranges <--

④ --> Generate Predictions <--

⑤ --> Launch Excel <--

⑥ --> Print Card <--

System Design...

For the system design process, you should assemble the following information:

- site plans (showing subsurface utilities, tanks, surface structures, etc.)
- plots of the subsurface (geologic cross-sections, water table maps, and soil boring and ground water sampling results)
- contaminant composition (or boiling point distribution)
- air permeability test data (permeability values & vapor concentrations)
- aquifer characteristics (ground water gradients, aquifer permeability, etc.)

① --> Launch Excel <--

② --> Print Card <--

③ --> Set Default BP Ranges <--

④ --> Generate Predictions <--

⑤ --> Launch Excel <--

⑥ --> Print Card <--

System Design...

At the right is a list of the components of a venting system design. Click on each to conduct the indicated phase of the design process.

Remember: It is not our intention to provide a generic recipe for vacuum extraction system design; instead we suggest the following as a structured thought process. As you shall see, even in a structured thought process, intuition and experience play important roles. There is no substitute for a good fundamental understanding of vapor flow processes, transport phenomena, and ground water flow!

- ☐ Number of Extraction Wells
- ☐ Well Location
- ☐ Well Construction
- ☐ Surface Seals
- ☐ Groundwater Pumping System
- ☐ Vapor Treatment

System Monitoring...



The performance of a soil venting system must be monitored in order to ensure efficient operation, and to help determine when to shut off the system.

At a minimum, the items listed to the right should be measured. "Click" on any one to get more information...

- ☐ Date and Time
- ☐ Vapor Flow Rates
- ☐ Pressure/Vacuum Readings
- ☐ Vapor Concentrations & Compositions
- ☐ Temperature
- ☐ Water Table Level
- ☐ Soil Gas Concentration & Composition

System Shut Down...

Target soil clean-up levels are often set on a site-by-site basis, and are based on the estimated potential impact that any residual may have on air quality, groundwater quality, or other health standards. They may also be related to safety considerations (explosive limits).

Generally, confirmation soil



- ☐ Cumulative Amount Removed
- ☐ Extraction Well Vapor Concentration
- ☐ Extraction Well Vapor Composition
- ☐ Soil Gas Data
- ☐ Soil Boring Data

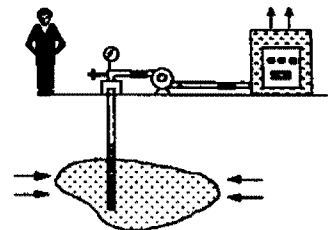
Economics...



"Click" on any item below (& hold button down) to see costs associated with that item.

For typical service station sites, clean-up costs can range from \$100K - \$250K for the venting operation alone, depending on the complexity of the site, clean-up time, permitting requirements, and the type of vapor treatment system used.

The two major costs are generally associated with the vapor treatment unit and



Acknowledgements...

This guidance system was originally conceived when the author decided to create a sample application to demonstrate the usefulness of "Hypertext" systems as vehicles for technology transfer. It is up to the users of this program to judge how well that goal has been achieved.

Since its conception, the system's scope and capabilities expanded and the project took on a life of its own. Not liking the very little situation the author was able to give during normal business hours, it was soon placing severe demands on the



Appendix B: "Soil Venting Help Stack" stack cards.

Help: Stack Information

Buttons

Buttons have been placed in each card. Clicking on any button will perform an action, such as:



Go Home to first card in Venting Stack



Go to next card



Go to Help card



Print card or text field

Calculate Perform a Calculation

When curious, click on Symbols, Pictures or Text.

Fields

Fields may contain information, or they may be a place for you to input numbers.

Scrolling Field:

Click on arrows to move text up or down

Click on the arrows, or move the box up or down with the mouse.

In this area, you can

Boxed Data Field:

When you see an I-beam cursor appear in a boxed field, click the mouse in the box to set the cursor. Then you may enter data.

A button will then usually be pushed to perform an action or calculation.

Try this example:

Enter Number in Box

1 inches

Click for calculation

2.54 centimeter

Return

H1

Help: About Soil Venting

More information about soil venting can be found in the following articles:

M. C. Mailey and G. B. Hoag, Induced Soil Venting for the Recovery/Restoration of Gasoline Hydrocarbons in the Vadose Zone, NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, TX, 1984.

P. C. Johnson, M. W. Kemblowski, and J. D. Colthart, Practical Screening Models for Soil Venting Applications, NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater, Houston, TX, 1984.

N. J. Hunter, B. E. Murphy, and J. S. Clarke, State of Technology Review: Soil Vapor Extraction Systems, U.S.E.P.A., CR-814319-01-1, 1988.

D. J. Wilson, A. N. Clarke, and J. H. Clarke, Soil Clean-up by in-situ Aeration. I. Mathematical Modelling, Sep. Science Tech., 23:991-1037, 1988.

H2

Return

Print References

Help: In-Situ Soil Venting System Design Process

This is the decision process that one must follow to:

1) decide if soil venting is applicable at a given site

&

2) design an effective soil venting system

It is an abridged version of Figure 2 in "A Practical Approach to the Design, Operation, & Monitoring of In-Situ Soil Venting Systems", by P. C. Johnson, C. C. Stanley, M. W. Kemblowski, J. D. Colthart, and D. L. Byers.

Return

H3

Help: Preliminary Site Investigation

More information about site investigation and remediation can be found in the following articles:

API Publication 1628

"A Guide to the Assessment and Remediation of Underground Petroleum Releases",

American Petroleum Institute, 1220 L Street Northwest, Washington DC, 20005

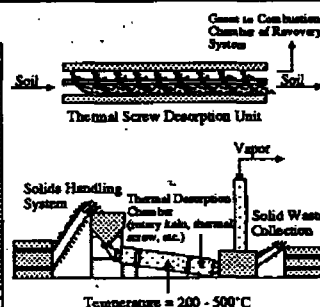
Return

H4

Help: Thermal Desorption

Process Description

In a thermal desorption treatment process, soils contaminated with volatile/semi-volatile organics are heated, and the volatilized contaminants are stripped with air, steam, or combustion products (burner flue gases) at relatively modest temperatures compared with incineration (200-500°C versus 1000-1200°C). The desorbed organic contaminants are



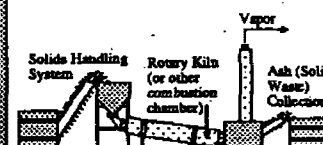
Return

H5

Help: Incineration

Process Description

Incineration, or the thermal destruction of wastes, is a complete destruction technology that can be used to treat soils contaminated with a wide range of hazardous organic wastes. Contaminated soils, sludges, or liquid wastes are added to a high-temperature combustion chamber (rotary kiln, fixed hearth, multiple hearth, fluidized bed, liquid



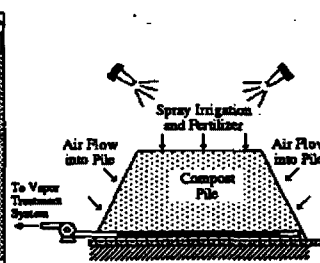
Return

H6

Help: Composting

Process Description

Composting is an above-ground soil management technique in which amended soil, containing organic wastes, is placed in large piles and aerated. The aeration enhances microbial degradation by providing oxygen to the soil/waste. With time, the decomposed waste is reduced in weight and volume, and the process produces a stabilized, enriched, humus-like material.



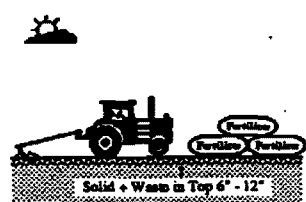
Return

H7

Help: Land Farming

Process Description

"Landfarming" refers to the practice of spreading organic wastes over an area of land, then relying on natural microbial action to degrade the waste. It is a widely accepted and cost-effective practice for the treatment of petroleum hydrocarbons, chlorinated compounds, and pesticides. In this process soil-associated microorganisms (bacteria and



Return

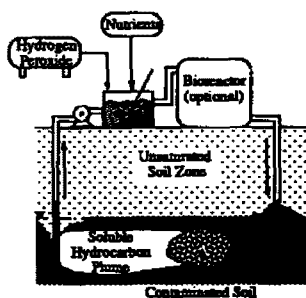
H8

Help: In-Situ Biostimulation

Process Description

Treatment of groundwater and soil contamination below the water table

("saturated zone") by in-situ biostimulation involves the addition of nutrients and/or O₂ (usually as H₂O₂ or liquid O₂) to an aquifer in order to enhance the degradation of the hydrocarbons by indigenous soil microbes. The nutrients and oxygen are added above ground to



Return

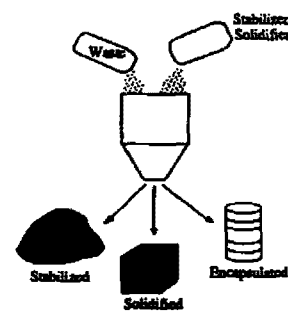
H9

Help: Solidification / Stabilization

Process Description

Stabilization and solidification are treatment processes designed to either improve waste handling and physical characteristics, decrease surface area across which pollutants can leach, or limit the solubility of hazardous constituents. When discussing this technology, the following definitions are common:

Solidification.



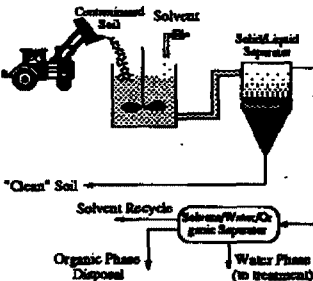
Return

H10

Help: Solvent Extraction / Soil Washing

Process Description

"Solvent extraction" is the process by which contaminants are removed from soils or sludges by mixing them with a solvent into which the contaminants preferentially partition. Which solvent is used for any particular treatment is very dependent upon the type of contaminant present in the soil. The solvent should have a high affinity for the contaminant(s) of



Return

H11

Help: Decision Matrix

- applicable
- potentially applicable, but not conclusively demonstrated

(1) - Different compounds will vary in their degree of biodegradability. Larger compounds typically have slower degradation rates.

(2) - Free-liquid pumping is only applicable when the residual contamination level is so high that contaminants freely drain from the soil.

	Biodegradation (1)	Free-liquid pumping (2)	Product recovery (3)	Free-liquid pumping (4)	Soil washing/extraction (5)	Stabilization/solidification (6)	Thermal desorption (7)	Verification
Aviation Fuel								
Crude Oil								
Gasoline								
Lead								
Metals, Salts								
Petrochemicals								
Pesticides								
PCB's								
Volatile Solvents								

Return

H12

Help: Soil Permeability

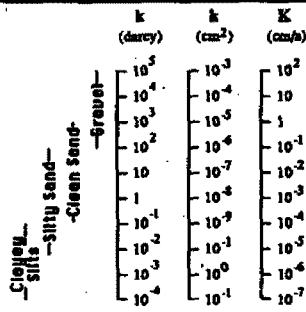
Note that k denotes the "permeability" of a porous media, while K represents the "hydraulic conductivity". The two are related by:

$$K = k \frac{\rho H_2O g}{\mu H_2O}$$

where:

- g = acceleration due to gravity (980 cm/s²)
- μ_{H_2O} = viscosity of water (0.01 g/cm-s)
- ρ_{H_2O} = density of water (1.0 g/cm³)

When choosing permeability values it is important to keep in mind that k (or K) often varies by several orders of magnitude over small distances. For this



See Conversion Tables

Return to Flowrate Calculation

H13

Help: Vapor Flowrate per Unit Well Thickness

The equation below is the steady-state, one-dimensional, radial flow solution to a vertical well. While simplistic, it generally provides good estimates for vapor flowrates. Its accuracy is, of course, limited by the accuracy of the values you input. In particular, the greatest uncertainty is usually associated with the soil permeability, which can vary by several orders of magnitude over small distances.

$$\frac{Q}{H} = \frac{\pi k P_v}{\mu} \frac{[1 - (P_{atm} / P_v)^2]}{\ln (R_v / R_1)}$$

- k = soil permeability to air flow (cm²) or (darcy)
- μ = viscosity of air = 1.8×10^{-4} g/cm-s or 0.018 cp
- P_v = absolute pressure at extraction well (g/cm-s²) or (atm)
- P_{atm} = absolute ambient pressure = 1.01×10^6 g/cm-s² or 1 atm
- R_v = radius of vapor extraction well (cm)
- R_1 = radius of influence of vapor extraction well (cm)
- H = thickness of well screen interval, or permeable soil zone (choose smallest value)

Return

H14

Help: Unit Conversion (k and K)

- Enter value of hydraulic conductivity or permeability to be converted
- Choose initial units
- Choose final units - (click for each calculation)

1 cm² = 9.78374 x 10⁻⁴ cm/s

Convert From

- cm/s
- ft/d
- cm²
- darcy

Convert To

- cm/s
- ft/d
- cm²
- darcy

Return

H15

Help: Compound List

Weathered Gasoline

View Only Mode

Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 25°C
1 propane	0.00	44.1	8.5
2 isobutane	0.00	58.1	2.93
3 n-butane	0	58.1	2.11
4 trans-2-butene	0	56.1	1.97
5 cis-2-butene	0	56.1	1.79
6 3-methyl-1-butene	0	70.1	0.96
7 isopentane	0.0069	72.2	0.78
8 1-pentene	0.0005	70.1	0.7
9 2-methyl-1-butene	0.0008	70.1	0.67
10 2-methyl-1,3-butadiene	0.0000	68.1	0.65

1.00000 = Sum of Mass Fractions (should be =1)

How Do I Measure a Distribution?

Return to Vapor Conc. Estimation Card

Print List

H16

Summary Card: Site Characterization

A complete site assessment must determine the following:

Subsurface Characteristics

- soil stratigraphy
- characteristics of distinct soil layers (permeability estimates, soil types)
- depth to groundwater
- groundwater gradient
- seasonal water table fluctuations
- aquifer permeability (estimate)
- subsurface & above-ground temperature

Contaminant Delineation

- extent of free-phase hydrocarbon
- distribution of contaminant in vadose zone
- distribution of contaminant in saturated zone
- extent of soluble contaminant plume
- composition of contaminants
- soil vapor concentrations (optional)

For more info see: API Publication 1628

"A Guide to the Assessment and Remediation of Underground Petroleum Releases", American Petroleum Institute, 1220 L Street Northwest, Washington DC, 20005



Return

H17

Compound List Default Data

#	Compound Name	Boiling Point		Vapor Pressure		New Vapor Pressure		Mass Fraction Data	
		Molecular Weight (gm)	(°C)	(mm Hg)	(mm Hg)	(mm Hg)	(mm Hg)	All to Gasoline	"Peak" Gasoline
1	propane	44.1	-42	8.5	8.5	0.00	0.0001	0.00	
2	isobutane	58.1	-12	2.93	2.93	0.00	0.0122	0.00	
3	n-butane	58.1	-1	2.11	2.11	0.00	0.0629	0	
4	trans-2-butene	56.1	1	1.97	1.97	0.00	0.0007	0	
5	cis-2-butene	56.1	4	1.79	1.79	0.00	0.0000	0	
6	3-methyl-1-butene	70.1	21	0.96	0.96	0.00	0.0006	0	
7	isopentane	72.2	28	0.78	0.78	0.00	0.1049	0.0069	
8	1-pentane	70.1	30	0.7	0.7	0.00	0.0000	0.0005	
9	2-methyl-1-butene	70.1	31	0.67	0.67	0.00	0.0000	0.0008	
10	2-methyl-1,3-butadiene	68.1	34	0.65	0.65	0.00	0.0000	0.0000	

Return

Print List

H18

Help: Data for Fortran Program

#	Compound Name	Boiling Point		Vapor Pressure		Organic Carbon Dist. Coeff	Mass Fraction Dist.
		Molecular Weight (gm)	(°C)	(mm Hg)	(mm Hg)		
1	propane	44.1	-42	8.5	8.5	73	0.00
2	isobutane	58.1	-12	2.93	2.93	49	0.00
3	n-butane	58.1	-1	2.11	2.11	61	0
4	trans-2-butene	56.1	1	1.97	1.97	430	204
5	cis-2-butene	56.1	4	1.79	1.79	430	204
6	3-methyl-1-butene	70.1	21	0.96	0.96	130	708
7	isopentane	72.2	28	0.78	0.78	48	1862
8	1-pentane	70.1	30	0.7	0.7	148	710
9	2-methyl-1-butene	70.1	31	0.67	0.67	155	525
10	2-methyl-1,3-butadiene	68.1	34	0.65	0.65	642	323

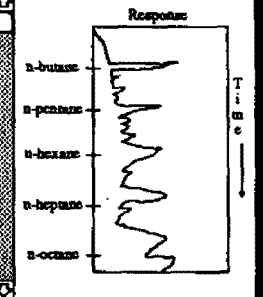
Return

H19

Help: How Do I Measure a Distribution?

Determining the exact composition of complex mixtures (such as gasoline) requires specialized analytical techniques. For the purpose of estimating the response in venting, however, an approximate composition can be used with very good results.

To determine an approximate distribution, one must analyze the mixture by gas chromatographic analysis. Prior to the analysis, choose about 6 - 10 marker compounds whose properties are well known. Often a series of straight chain alkanes (n-butane, n-pentane, n-hexane, etc.) is chosen. Then the unknown mixture is analyzed, and the areas of all peaks eluting between the retention times of two known peaks are summed and treated as one of the known peaks, as illustrated on the



Return to Vapor Conc. Calc.

Calculate a Distribution

Help: Calculate a Distribution

Perform a GC analysis and sum all peaks whose retention times lie between the known compounds.

Enter the areas or concentrations in the appropriate location in the Table on the right. Then, Click Calculate.

Click the "Transfer Data..." button and your distribution will be copied to the Composition Table.

#	Compound	Concentration or Area	Normalized Distribution
1	propane	0.00	0.00000
2	n-butane	1000	0.07692
3	n-pentane	5000	0.38462
4	n-hexane	7000	0.53846
5	n-heptane	0.00	0.00000
6	n-octane	0.00	0.00000
7	n-nonane	0.00	0.00000
8	n-decane	0.00	0.00000
9	n-undecane	0.00	0.00000
10	n-dodecane	0.00	0.00000

Return Calculate

Return to Vapor Conc. Calc. Card

Return

Transfer Data to Distribution Card

Help: About Calculation

In this estimation of equilibrium (saturated) vapor concentrations, we assume that the contaminant concentrations are great enough (>200 mg/kg TPH) that it is distributed between vapor, sorbed, dissolved-in-soil, moisture, & free-phases. In this case, the equation at the right applies (look for "Raoult's Law" and the "Ideal Gas Law" in any thermodynamics textbook for references). We do correct for

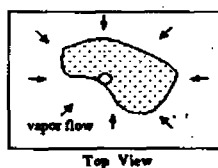
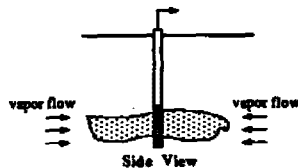
$$C_v = \sum_{i=1}^n \frac{x_i P_i^* M_{w,i}}{RT}$$

C_v = total vapor concentration (mg/l)
 n = number of components
 x_i = mole fraction of component i
 P_i^* = vapor pressure of component i (atm)
 $M_{w,i}$ = molecular weight of component i (mg/mole)
 R = Universal Gas Constant = 0.0821 l-atm/K-mole
 T = absolute temperature (K) = $T(^{\circ}C) + 273$

Return

H22

Help: 6a) Dilution Effects [Bypassing]

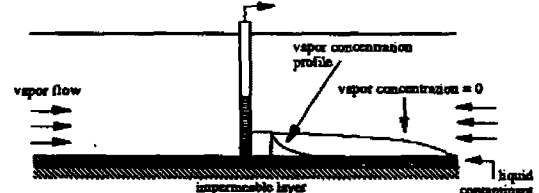


The figure above depicts the case where some vapors "bypass" zones of contamination, and therefore the vapors removed from the extraction well represent a mixture of the vapors obtained from both contaminated and clean vapor flowpaths. One can roughly judge the amount of bypassing by the well placement, screening, and contaminant distribution. Generally, observed vapor concentrations are roughly 10 - 50% of the ideal removed.

Return

H23

Help: 6b) Liquid Layers



In Figure 6b, vapor flows parallel to, but not through, the zone of contamination, and the significant mass transfer resistance is vapor phase diffusion. This would be the case for a layer of liquid hydrocarbon resting on top of an impermeable strata or the water table. This problem was studied by Johnson et al (1988 - NWWA/API Petroleum Hydrocarbons Conference) for

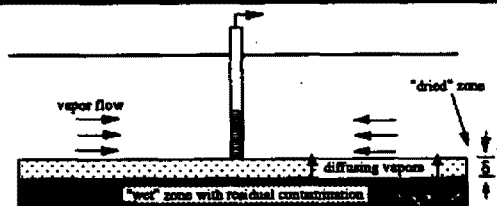
Show Me Equations

Return

Let's Do a Calculation

H24

Help: 6c) Low Permeability Lenses



In the situation depicted above, vapor flows past, rather than through the contaminated soil zone, such as might be the case for a contaminated clay lens surrounded by sandy soils. In this case vapor diffusion through the clay to the flowing vapor limits the removal rate (the removal rate actually becomes

Show Me Equations

Return

Let's Do a Calculation

Help: 6c) Low Permeability Lenses - Equations

$$R_{\text{est}} = \pi (R_2^2 - R_1^2) \sqrt{\frac{C_{\text{sat}} D_{\text{eff}} C_{\text{sat}} P_{\text{sat}}}{2t}}$$

$$\delta = \sqrt{\frac{C_{\text{sat}} D_{\text{eff}} t}{C_{\text{sat}} P_{\text{sat}}}}$$

where:

- R_{est} = estimated removal rate (mg/d)
- δ = thickness of "dried-out" zone (m)
- R_1 = defines region in which contamination is present (m)
- R_2 = defines region in which contamination is present (m)
- C_{sat} = estimated saturated vapor concentration (mg/m³)
- D_{eff} = effective soil vapor diffusion coefficient (m²/d)
- C_{sat} = initial residual level of contaminant in soil (mg/kg)
- P_{sat} = soil bulk density (kg/m³)
- t = time (d)

Derivations for these equations are given in Johnson, et al - "A Practical Approach to the Design, Operation and Monitoring of In Situ Soil Venting Systems" - 1990.

These Equations are valid for single-component

Let's Do a Calculation

Return

H26

Help: Default Boiling Point Ranges

The Fortran program HYPEVENT will report residual levels of compounds falling between user specified boiling point ranges. The default values have been chosen so that residual levels of compounds with boiling points between the following compounds are grouped together:

- Propane - Isopentane (-50 to 28 C)
- Isopentane - Benzene (28 to 80 C)
- Benzene - Toluene (80 - 111 C)
- Toluene - Xylenes (111 - 144 C)
- Xylenes - Methylanthralene (144 - 250 C)

Return

H27

Help: Boundary Layer Equations

$$R_{\text{est}} = \eta Q C_{\text{sat}}$$

$$\eta = \frac{1}{3H} (6D_{\text{eff}} \mu/k)^{1/2} [\ln(R_2/R_1)(P_{\text{atm}} - P_w)]^{1/2} \sqrt{R_2^2 - R_1^2}$$

The equation above estimates the removal rate from a layer of liquid product by a single well, based on a Boundary Layer Theory approach to the problem. It is not directly applicable to mixtures, because it

- R_{est} = estimated removal rate
- η = efficiency relative to maximum removal rate
- D_{eff} = effective soil vapor diffusion coefficient (cm²/s)
- μ = viscosity of air = 1.8×10^{-4} g/cm-s
- k = soil permeability to vapor flow (cm²)
- H = thickness of screened interval (cm)
- R_1 = radius of influence of venting well (cm)
- R_2 = venting well radius (cm)
- P_{atm} = absolute ambient pressure = 1.016×10^6 g/cm- δ^2
- P_w = absolute pressure at the venting well (g/cm- δ^2)
- $R_2 < R_1$ defines region in which contamination is present

Let's Do a Calculation

Return

H28

Help: Boundary Layer Equations - Calculation

1 Soil Type (choose one)

- ☐ Medium Sand
- ☐ Clayey Silts
- ☐ Silty Sand
- ☒ Fine Sand
- ☐ Input Your Own Permeability Range

to 10 [darcys]

2 Process Variables:

- 6.6 thickness of screened interval (ft)
- 40 radius of influence of venting well (ft)
- 2 venting well radius (in)
- 120 applied vacuum at well (in H₂O)
- 40 radial width of contaminated zone

Just enter values into the appropriate fields, then click on the "calculate" button.

The "Relative Efficiency" is the ratio of the predicted removal rate to the removal rate that would be obtained if the extracted vapors were saturated, or in equilibrium with the liquid

Relative Efficiency = 7.457548 to 23.582837 (%)

--> Calculate <--

Return

H29

Help: Low Permeability Lenses - Calculation

1 Process Variables:

- 4 venting well radius (in)
- 150 radial width of contaminated zone (ft)
- 10000 residual contaminant level (mg/kg)

2 Contaminant Properties:

- 84.2420 contaminant molecular weight (g/mole)
- 43.9584 contaminant vapor pressure (mm Hg)
- 18 temperature (C)

☐ use values already input from Card 10

Just enter values into the appropriate fields, then click on the "Calculate" button.

3 --> Calculate <--

Time (days)	Removal Rate (kg/d)	δ (m)
1	3263.553	0.062
7	1233.507	0.164
30	595.841	0.340
60	421.323	0.481
120	287.220	0.681
180	243.251	0.824
240	210.661	0.953
360	172.004	1.179
540	140.441	1.444
720	121.625	1.668
1080	99.307	2.043

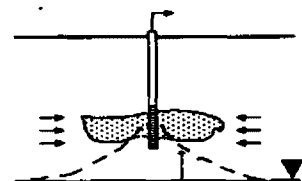
Return

H30

Ground Water Table Upwelling

During venting, the pressure within the radius of influence of the vapor extraction well is lowered, due to the applied vacuum. This lowering of the pressure affects the groundwater level in this zone, and an "upwelling", or local rise in the water table will occur.

The local water table rise can be as great as the gauge vacuum applied at the extraction well



Ground Water Level Before Start of Venting Ground Water Level After Start of Venting

Return

H31

Date and Time...

Generally, the DATE and TIME should be recorded along with any measurement that is made. Given the time scale for venting-related processes, recording the time to the nearest minute should be sufficient.

Sample devices are Rolex watches, hour glasses, sun dials, and timers.



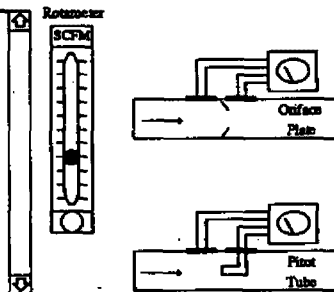
Return

H32

Vapor Flow Rates...

Vapor flow rates from each extraction well and into any injection wells should be monitored.

Sample measuring devices include pitot tubes, orifice plates and rotameters. It is important to have calibrated these devices at the field operating pressures and temperatures



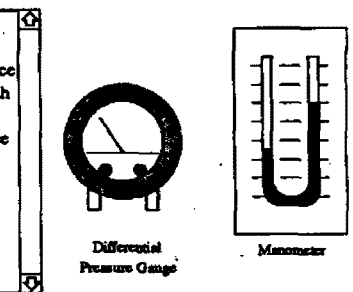
Return

H33

Pressure/Vacuum Readings...

Pressures/Vacuums should be measured at each extraction and injection well. In addition, subsurface pressure distributions (measured with vadose zone installations) are useful for determining the zone of influence and vapor flow paths.

Typical pressure/vacuum measuring devices include manometers and differential pressure gauges.



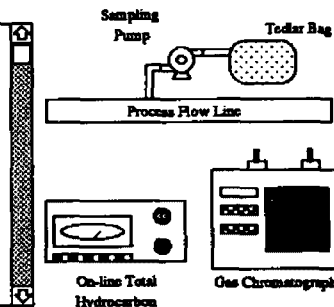
Return

H34

Vapor Concentrations & Composition...

The vapor concentration and composition from each extraction well should be analyzed periodically. This data is multiplied by the extraction well flowrate to calculate the removal rate (i.e. lb/day), and cumulative amount of contaminant removed.

By itself, vapor concentration data does not give a complete picture of the system's performance. Decreases

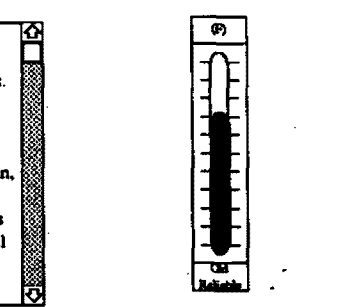


Return

H35

Temperature...

The soil and ambient temperatures can have a significant effect on the performance of soil venting systems. The soil temperature affects the contaminant vapor concentrations, while the ambient temperature controls whether or not condensation, or even freezing will be significant. For future reference, therefore, it is useful to record the ambient and soil temperatures.

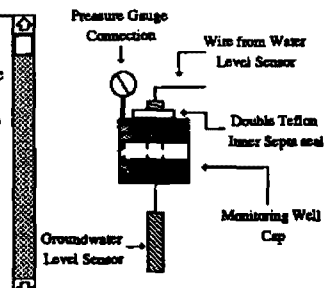


Return

H36

Water Table Level... (for contaminated soils located near the water table)

Whenever the contaminated zone lies near the groundwater table (within 3 to 5 ft), it is important to monitor the water table level to ensure that contaminated soils remain exposed to vapor flow. Measuring the water table level during venting is not a trivial task because the monitoring well must remain sealed. Uncapping the well releases the vacuum and any effect that it has on the water table level.



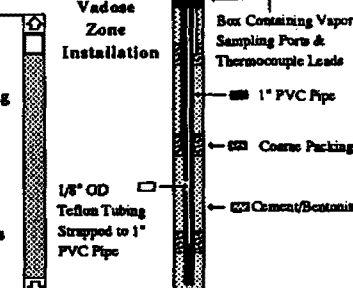
Return

H37

Soil Gas Concentration & Composition...

These should be measured periodically at different radial distances from the vapor extraction well(s). Data from soil gas sampling is valuable for three reasons:

(1) by comparing extraction well concentrations with soil gas concentrations, it is possible to estimate the fraction of vapor that is flowing through the contaminated zone (i.e. the "efficiency" of



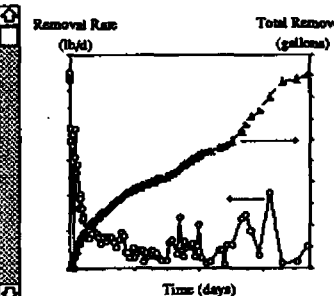
Return

H38

Cumulative Amount Removed...

CUMULATIVE AMOUNT REMOVED

is determined by integrating the measured removal rates (flowrate x concentration) with time. While this value indicates how much contaminant has been removed, it is usually not very useful for determining when to take confirmation borings unless the original spill mass is known very accurately. In most cases that



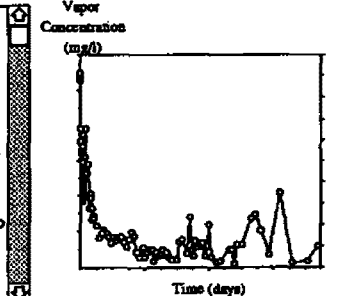
Return

H39

Extraction Well Vapor Concentration...

EXTRACTION WELL VAPOR CONCENTRATION

the vapor concentrations are good indications of how effectively the venting system is working, but decreases in vapor extraction well concentrations are not strong evidence that soil concentrations have decreased. Decreases may also be due to other phenomena such as water table level increases, increased mass transfer resistance



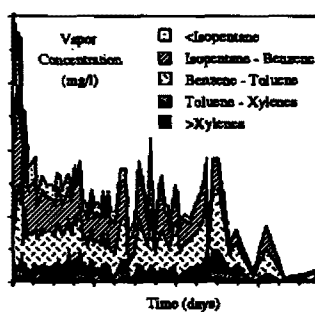
Return

H40

Extraction Well Vapor Composition...

EXTRACTION WELL VAPOR COMPOSITION

when combined with vapor concentrations this data gives more insight into the effectiveness of the system. If the total vapor concentration decreases without a change in composition, it is probably due to increased mass transfer resistance (water table upwelling, drying-out of low permeability zones, etc.), and is not



Return

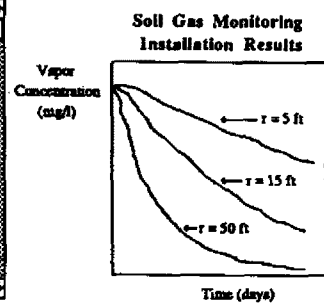
H41

Soil Gas Data...

SOIL GAS DATA

this data is the most useful because it yields information about the residual composition and extent of contamination.

Vapor concentrations can not, in general, be used to determine the residual level, except in the limit of very low residual levels (when vapor concentrations are proportional to soil residual levels).



Return

H42

Soil Boring Data...

SOIL BORING DATA

Generally confirmation soil borings are taken once a system is turned off, and these are often analyzed for TPH (total petroleum hydrocarbons) and volatile residuals.

One should keep in mind that TPH results can often be misleading, since they reveal nothing about the composition of the residual or its

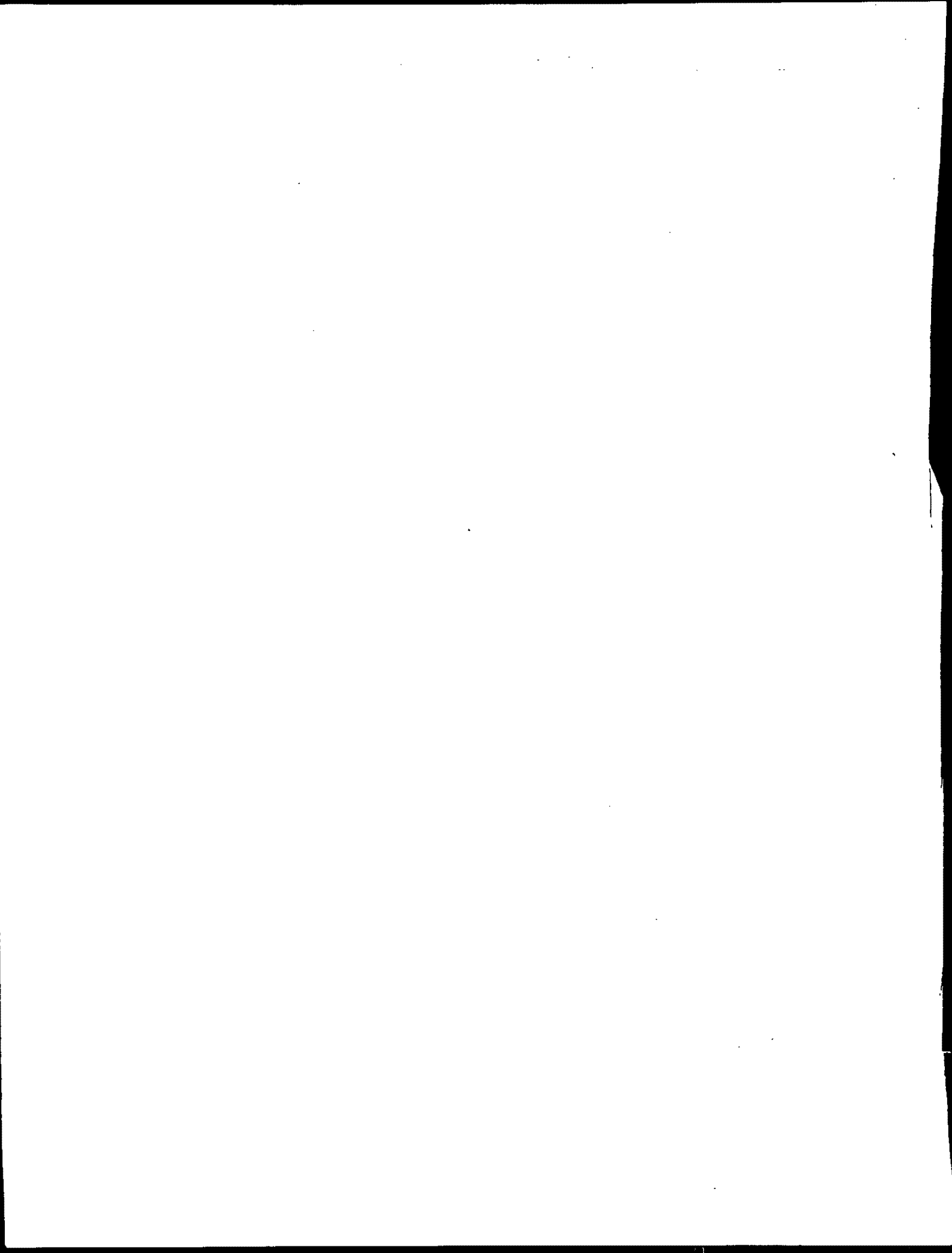
Soil Boring Results

Boring Location	TPH (mg/kg)	BTEX (mg/kg)
Before		
B-1	1200	20
B-2	14000	120
B-3	8600	400
After		
B-4	20	ND
B-5	120	0.1
B-6	5	ND

Return

H43

Appendix C: "Air Permeability Test" stack cards.



Air Permeability Tests...

The purpose of an air permeability test is to obtain site-specific data that will be used in the final system design. It is a way to verify that venting is an appropriate remediation technique for your site.

In particular, one typically tries to get a better estimate of the soil permeability of each distinct soil layer to be treated, and a better estimate of contaminant vapor concentrations.

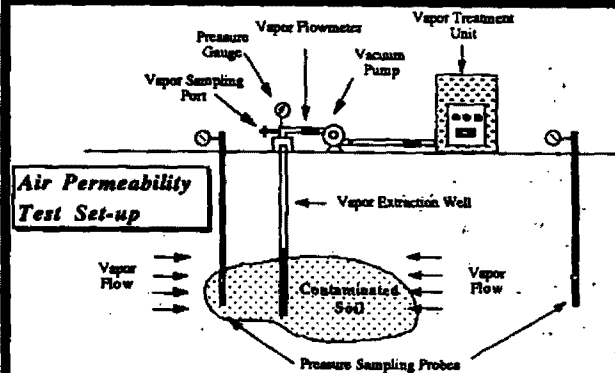
Show Me Set-Up

Test Instructions

Data Analysis

Return to Main Stack - Card 21

AP1



Print Card

Return

AP2

Air Permeability Test - Instructions

1) Identify soil zones to be treated

2) Install vapor extraction well(s) in this zone(s). Existing monitoring wells may be used, when the screen interval extends only into the zone to be treated. Note the extraction well radius and borehole size. Insure that the well is not "connected" to other soil zones through the borehole (use cement/grout to seal annular borehole)

show me sample data

Pore Volume Estimation:

Enter:

- 1) Soil Layer Thickness (ft): 6.6
- 2) Estimated Radius of Influence (ft): 50
- 3) Air Perm. Test Flowrate (CFM): 15

--> Calculate <--

Pore Volume: 15563 ft³
Time to Extract a Pore Volume: 0.72 days

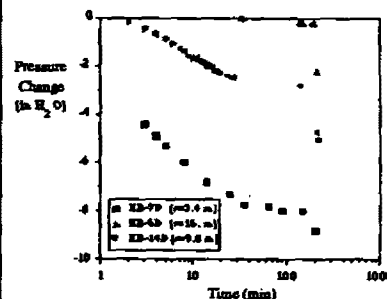
Return

AP3

Air Permeability Test - Sample Data

Pictured at the right are the soil vacuum measurements from an air permeability test conducted in a silty sand.

The specific operating conditions and site characteristics are described in "A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems", by P. C.



Return

AP4

Air Permeability Test - Data Analysis

The expected decrease in subsurface pressure (increase in gauge vacuum) P' is predicted by: (see Johnson et al [1990] for derivation)

$$P'(r,t) = \frac{Q}{4\pi m(k/\mu)} \int_{\frac{r^2}{4kt}}^{\frac{r^2}{4kt} + \frac{4kt}{m^2}} \frac{e^{-x}}{x} dx$$

p = gauge vacuum
 m = screen thickness
 r = radial distance from extraction well
 k = soil permeability
 μ = air viscosity = 0.018 centipoise

ϵ = air-filled void fraction
 t = time
 Q = volumetric flowrate from extraction well
 P_{atm} = ambient atmospheric pressure

Skip the Explanation

Return

AP5

Air Permeability Test - Data Analysis (cont.)

For $(r^2/\mu k P_{atm} t) < 0.1$, the governing equation can be approximated by the expression:

$$P' = \frac{Q}{4\pi m(k/\mu)} \left[-0.5772 - \ln\left(\frac{r^2 \epsilon \mu}{4 k P_{atm}}\right) + \ln(t) \right]$$

This Equation predicts that a plot of P' vs- $\ln(t)$ should be a straight line with slope A and y-intercept B equal to:

$$A = \frac{Q}{4\pi m(k/\mu)} \quad B = \frac{Q}{4\pi m(k/\mu)} \left[-0.5772 - \ln\left(\frac{r^2 \epsilon \mu}{4 k P_{atm}}\right) \right]$$

Return

AP6

Air Permeability Test - Data Analysis (cont.)

The permeability, k , can then be calculated by one of two methods:

① The first is applicable when both Q (flowrate) and m (well screen interval) are known accurately. The calculated slope A is used:

$$k = \frac{Q \mu}{4 A \pi m}$$

② The second approach is used whenever Q or m are not known with confidence. In this case, both the slope, A, and intercept, B, are used:

$$k = \frac{r^2 \epsilon \mu}{4 P_{atm}} \exp[0.5772 + \frac{B}{A}]$$

Return

AP7

Air Permeability Test - Data Analysis (cont.)

Enter radial distance of monitoring points		r = 33 (ft)		r = 32.4 (ft)		r = (ft)	
(min)	(in H2O)	(min)	(in H2O)	(min)	(in H2O)	(min)	(in H2O)
9	0.1	4	1.2				
11	0.2	7	3				
15	0.2	9	4.3				
23	0.4	12	5.5				
30	0.7	16	6.9				
40	1.3	24	9.9				
100	2.8	30	11				
		39	13				
		52	16				
		77	20				
a) flowrate		b) screen interval thickness		c) flowrate		d) screen interval thickness	
15 (SCFM)		6.6 (ft)					
--> Calculate <--		k = 18.6948 darcy (A)		k = 2.85845 darcy (A)		k = darcy (A)	
		k = 9.29866 darcy (B)		k = 7.76759 darcy (B)		k = darcy (B)	

Return

Explanation & Statistics

AP8

Air Permeability Test - Data Analysis (cont.)

On the previous Card (AP8), the data you input were fit to the approximate expression given on Card AP6. It was analyzed using both methods described on card AP7, if you input values for the extraction well flowrate (Q) and the stratum thickness (m). Below each column of data, the two calculated permeability values are denoted by:

darcy(A) - refers to calculation method 1 (see Card AP7)
 darcy(B) - refers to calculation method 2 (see Card AP7)

During the regression analyses, the data expressed as pairs of points ($\ln(t), P$) are fit to a line. The "correlation coefficient", r , is a measure of how well the data conform to the theoretical curve. As $r \rightarrow 1$, the data points all fall on the theoretical curve. At the right are given the correlation coefficient values for the three data sets. For more info on the meaning of r , consult any introductory Statistics book.

Correlation Coef.

(r)

data set #1

data set #2

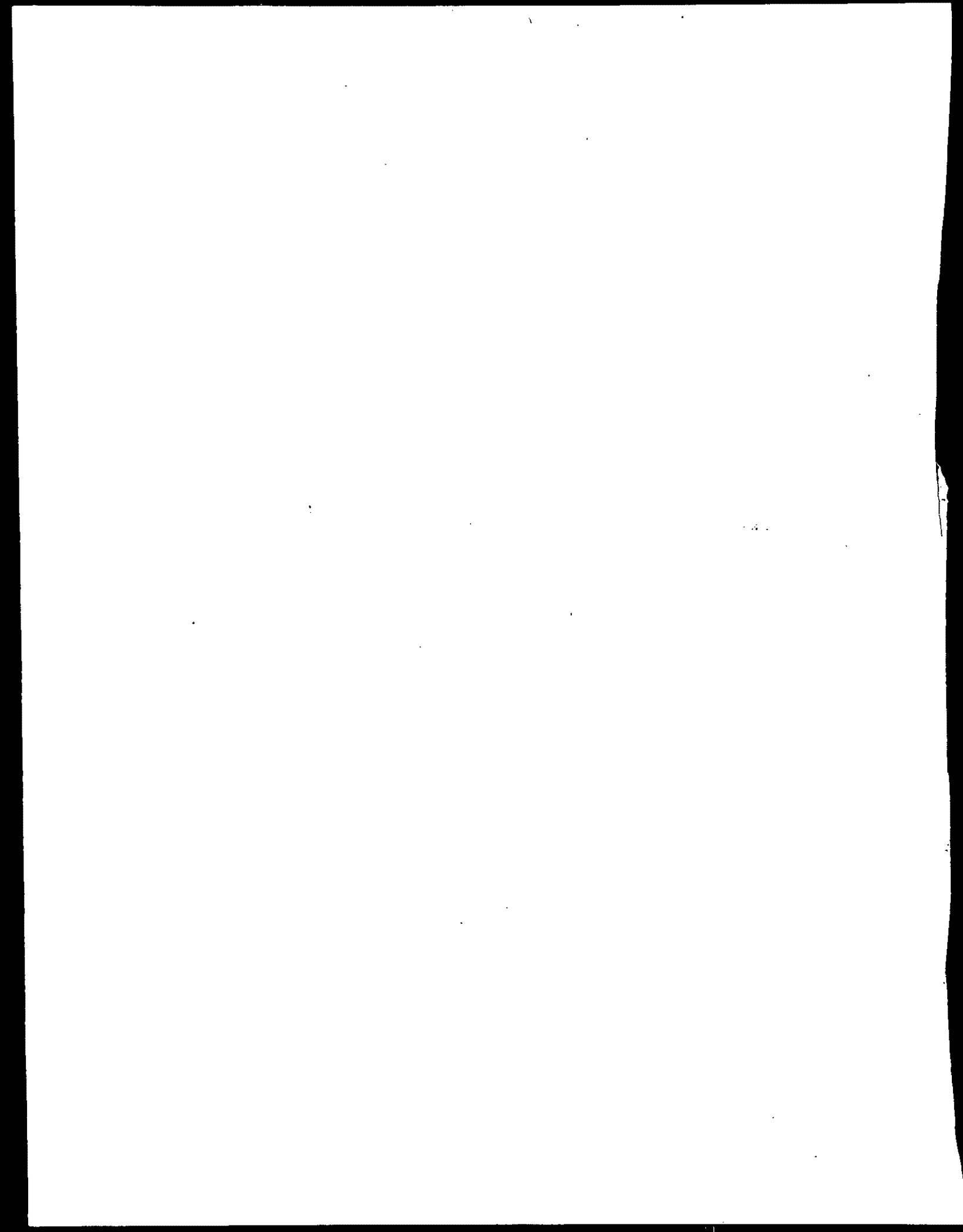
data set #3



[Return](#)

AP9

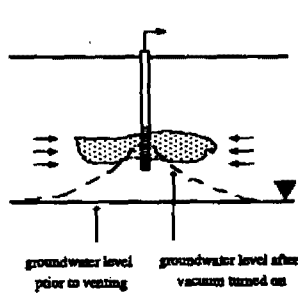
Appendix D: "Aquifer Characterization" stack cards.



Aquifer Characterization:

To achieve efficient venting, the hydrocarbon-contaminated soil must be exposed to air flow, therefore, in most cases where the residual soil contamination lies close to, or below, the saturated soil zone (groundwater table), it will be necessary to incorporate a groundwater pumping system in the vapor extraction system design.

As mentioned previously, one must always be aware of the groundwater



groundwater level prior to venting groundwater level after vacuum turned on

Return to Main Stack

AC1

Aquifer Characterization:

Since most venting systems are installed above "phreatic aquifers" (aquifers with unconfined upper surfaces), the two primary aquifer parameters needed for design are:

K = hydraulic conductivity

S = effective porosity (or specific yield)

The first parameter represents a convenient combination of the fundamental parameters: permeability, density, and viscosity:

$$K = \frac{k \rho g}{\mu}$$

where:

k = permeability

ρ = fluid density

g = acceleration due to gravity

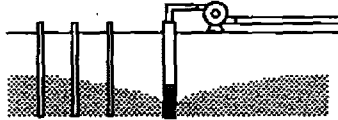
μ = viscosity

Return to Main Stack

AC2

Aquifer Characterization:

These parameters (K and S) can be estimated using the results of a standard transient groundwater pump test with a constant pumping rate. The results are then compared against standard "type curves" for specific aquifer situations (i.e. leaky, unconfined aquifers, etc.).



Press the "References" button below for more information on slug tests, bail tests, pump tests, and data analysis.

References

Return to Main Stack

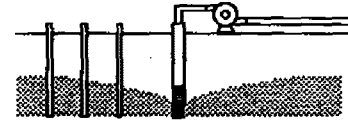
AC3

Aquifer Characterization - References

J. Bear, "Hydraulics of Groundwater", McGraw-Hill, 1979, ISBN 0-07-004170-9, p. 463 - 490.

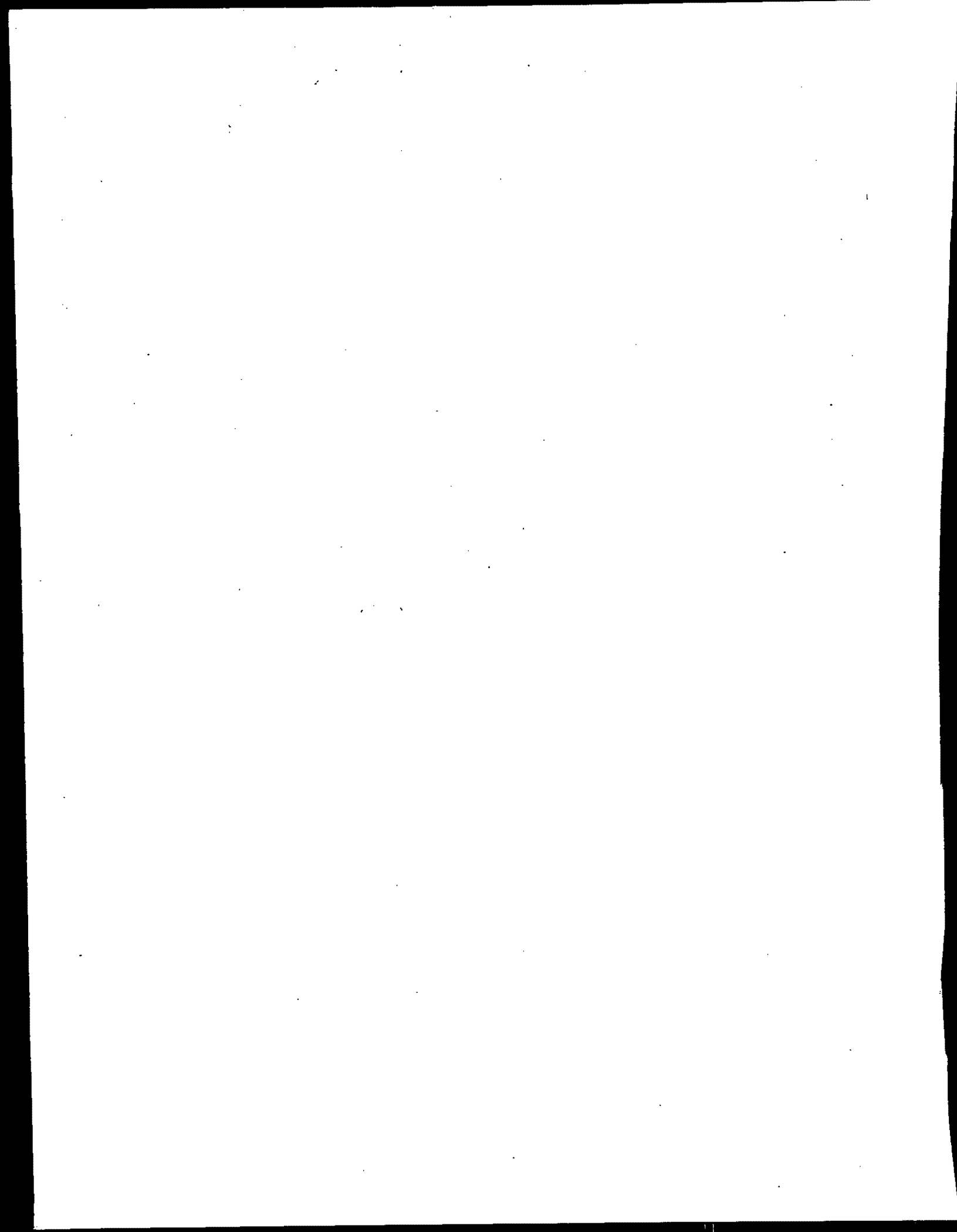
R. A. Freeze and J. A. Cherry, "Groundwater", Prentice-Hall, 1979, ISBN 0-13-365312-9, p. 339 - 352.

G. B. Chidlin, "A Critique of the Horne Method for Slug Test Analysis: The

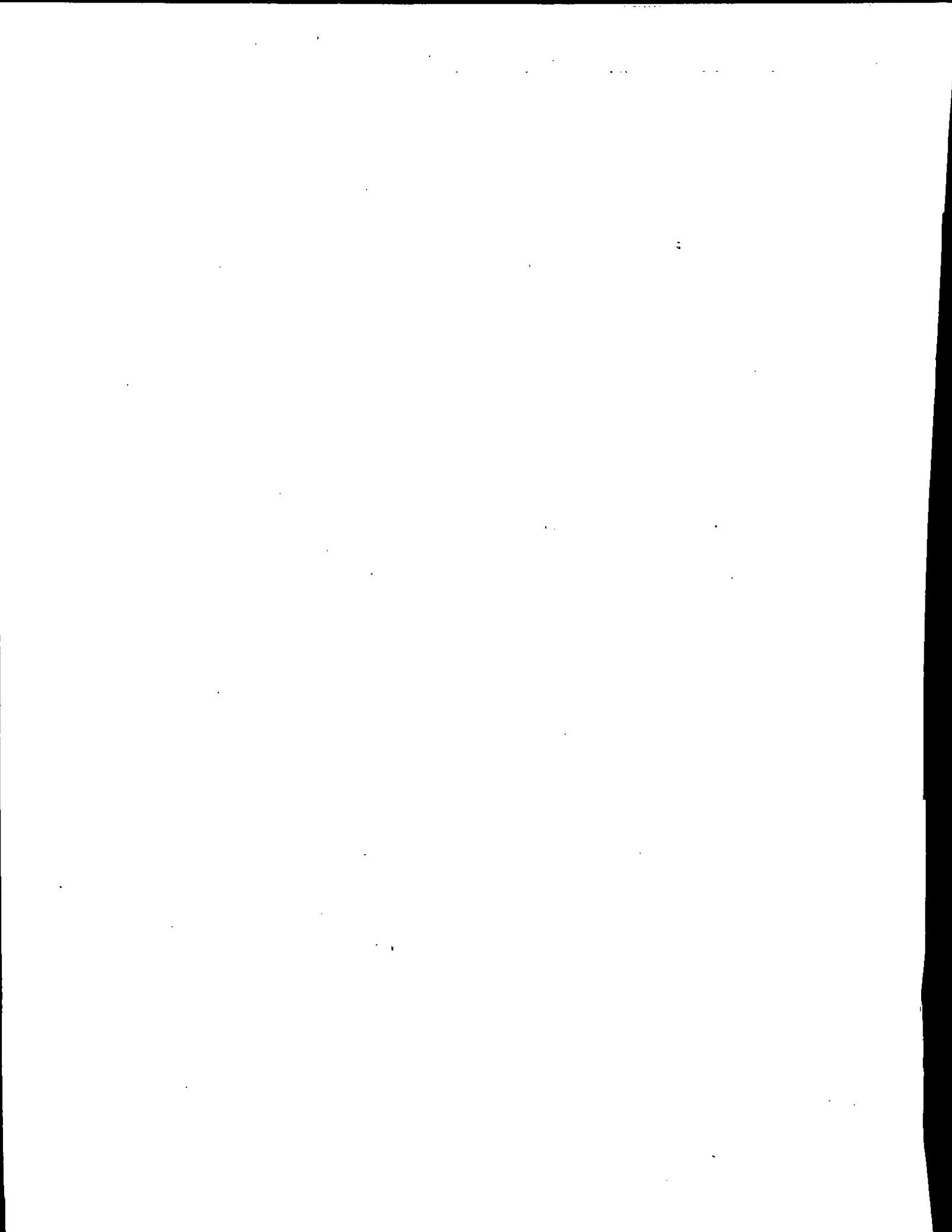


Return

AC4



Appendix E: "System Design" stack cards.

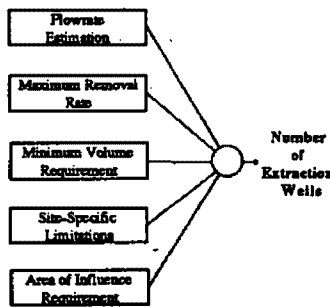


Number of Venting Wells...

The procedure for estimating the required number of extraction wells is similar to the process used previously to determine if venting is appropriate at a given site.

As illustrated at the right, we will estimate single vertical well flow rates, calculate the minimum vapor flow required, determine the areal extent of influence, and then factor in any site-specific limitations. This information then determines the necessary number of extraction wells.

Just proceed to follow the steps dictated on the following cards-->



Return

SD1

Design Input

(soil stratigraphy & contaminant characteristics)

Select the total mass ☒ [kg] ☐ [lb]

Please enter the required information for each distinct soil layer, click on the "Update" button, and then proceed to the next card (i.e. click on right arrow at bottom). (the tab key can be used to move between cells)

Clear All Entries

Description of Soil Unit	Depth BGS* (ft)	Description of Contaminant	Contaminant Distribution			Calc. Total Mass (kg)
			radius (ft)	interval thickness (ft)	average conc. (mg/kg)	
1. Medium Sand	10 to 30	gasoline	20	20	100	128.9
2. Clayey Sil.	20 to 43	gasoline	20	13	1000	786.0
3. Fine Sand	43 to 50	gasoline	20	7	10000	4232.3
4.						0.0
5.						0.0
6.						0.0
7.						0.0
8.						0.0

* Below Ground Surface

Update

Return

SD2

Design Input

Please enter the required information for each distinct soil layer, and then proceed to the next card.

Note: - click on any table heading to get more info
- use tab key to move between cells

- ☐ Medium Sand
- ☐ Fine Sand
- ☐ Silty Sand
- ☐ Clayey Silts

Description of Soil Unit	Permeability* (darcy)	Design Vacuum (in H2O)	Extraction Well Construction			Critical Volume of Air** (L/g)	Efficiency (%)
			well radius (in)	screen thickness (in)	radius of influence (ft)		
1. Medium Sand	10	100	40	2	10	40	128.48
2. Clayey Sil.	0.01	1	40	2	3	40	128
3. Fine Sand	1	10	40	2	3	40	128
4.							100
5.							
6.							
7.							
8.							

* Enter or choose from list at top right

** minimum volume of vapor required to achieve remediation

Clear All Entries

Return

SD3

Design Input

Please enter (1) the desired time period for remediation, (2) the design gauge vacuum, and then (3) click the "update" button.

Note: - click on any table heading to get more info
- use tab key to move between cells

Update

Description of Soil Unit	Time for Clean-up (days)	Design Vacuum (in H2O)	Flowrate per Vapor Extraction Well (SCFM)	Minimum Number of Wells			
				Based on Area	Based on Critical Volume**		
1. Medium Sand	180	40	38.4	9.2	9.0	9.2	9.2
2. Clayey Sil.	180	40	9.0	9.2	9.2	9.2	9.2
3. Fine Sand	180	40	1.9	9.2	3.3	9.2	24.6
4.			NA	NA	NA	NA	NA
5.			NA	NA	NA	NA	NA
6.			NA	NA	NA	NA	NA
7.			NA	NA	NA	NA	NA
8.			NA	NA	NA	NA	NA

NA - not enough input data

** minimum volume of vapor required to achieve remediation

Clear All Entries

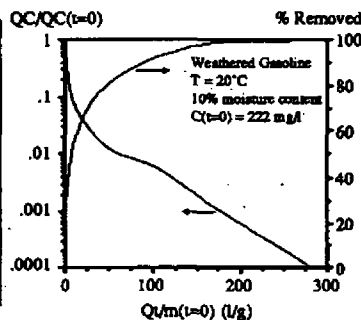
Return

SD4

Critical Volume Calculation...

Pictured at the right are the results of sample model predictions, for a weathered gasoline sample.

The vertical axis represents either normalized concentrations, or normalized removal rates, while the horizontal axis represents the total volume of vapor removed per initial mass of gasoline. Notice that the removal rate, and % removed curves resemble the behavior that is typically observed in venting operations.



Return to Design

Do a Calculation

SD5

Critical Volume Predictions...

Simply enter the temperature at the right, and then specify the composition of your contaminant. If you are unsure about this, click on the "About Composition..." button located at the lower right.

- Temperature (°C)
- Contaminant Composition (choose one):
 - ☐ Enter Distribution
 - ☐ "Fresh" Gasoline
 - ☒ "Weathered" Gasoline

View Distributions

--> Set Default BP Ranges <--

Boiling Point Range #1	50	to	28	°C
Boiling Point Range #2	28	to	80	°C
Boiling Point Range #3	80	to	111	°C
Boiling Point Range #4	111	to	144	°C
Boiling Point Range #5	144	to	250	°C

Generate Predictions

all the more about BP ranges...

SD6

About Composition...

Import Data

FIRST PRESS THE IMPORT DATA BUTTON

These are the results for the contaminant type that you have

Saturated Vapor Concentration at time t: [mg/L]
Min Volume to Remove >90% of Initial Residual: [L-air/g-residual]

Temperature (°C):
Contaminant Type:

Qt/m(t) [L-air/g-residual]	Vapor Conc. (% initial)	Residual Level (% initial)	BP #1 Residual (% total)	BP #2 Residual (% total)	BP #3 Residual (% total)	BP #4 Residual (% total)	BP #5 Residual (% total)
0.0	100.000	100.000	.690	11.650	24.010	22.140	41.510
.24	75.062	95.000	.123	9.263	23.982	23.000	43.632
.37	58.631	90.022	.000	6.755	23.474	23.820	45.950
.58	48.078	85.034	.000	4.512	22.403	24.577	48.509
1.49	39.390	80.034	.000	2.632	20.771	25.248	51.350
2.11	31.941	75.035	.000	1.222	18.503	25.766	54.509
2.87	25.916	70.035	.000	.385	15.556	26.031	58.028
3.81	21.150	65.037	.000	.068	12.052	25.919	61.959

Launch Excel

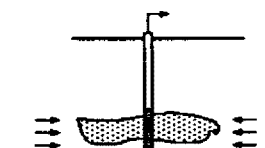
Return to System Design

Print Card

SD7

Removal Efficiency...

The subsurface is difficult to characterize, and rarely conforms to our notion of a "sandbox". There are three general classes of situations that will cause venting removal rates to be less than those predicted for the ideal case. Each of these are discussed in "A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil Venting Systems". You can learn more about each by clicking on the buttons in the right.



Dilution Effects

Liquid Layers

Low Permeability Lenses

Ground Water Upwelling

In addition, when contaminants are located close to ground water, the effect of the vacuum on the water table level can significantly impact a venting system's performance. To learn about this, click on the "Ground Water Upwelling" button.

Return

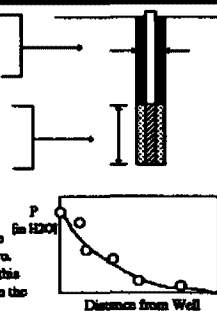
SD8

Help: Well Parameters

"Well Radius" - in general will be the radius of the well borehole, because the packing material is typically more permeable than the soil formation.

"Screen Thickness" is the length of the slotted interval of the well, or the thickness of the permeable zone, whichever is smaller.

"Radius of Influence" is the radial distance away from the extraction well, where the gauge pressure measured in the soil is approximately zero. The predictions are not very sensitive to this parameter, and most reported values lie in the range 40 - 120 ft.



Return to Design

SD9

Help: Minimum Number of Wells

The "Minimum Number of Wells" is calculated by the two methods discussed below:

a) Based on Area -

In this approach we estimate the minimum number of wells required to provide air flow through the contaminated zone as you have defined it. If R_c denotes the radial extent of contamination, and R_i denotes the "radius of influence" of an extraction well, then:

$$N_{wells} = \frac{R_c^2}{R_i^2}$$

b) Based on Critical Volume of Vapor -

In this approach we determine the number of wells required to extract the critical volume of vapor from the contaminated soil zone within the desired time frame. In this approach:

$$N_{wells} = \frac{V_{critical} M_{spill}}{Q_{well} \epsilon \Delta T}$$

Vertical = critical volume of vapor [L^3 -critical]

M_{spill} = spill mass [g-residual]

Q_{well} = volumetric flowrate from single well [L/d]

ϵ = efficiency of extraction process

ΔT = time for clean-up [d]

Return to Design

SD10

Contaminant Composition

Weathered Gasoline

View only Mode

Compound Name	Mass Fraction	Molecular Weight (g)	Vapor Pressure @ 20 °C
1 propane	0.00	44.1	8.5
2 isobutane	0.00	58.1	2.93
3 n-butane	0.00	58.1	2.11
4 trans-2-butene	0.00	56.1	1.97
5 cis-2-butene	0.00	56.1	1.79
6 3-methyl-1-butene	0.00	70.1	0.96
7 isopentane	0.00	72.2	0.78
8 1-pentene	0.00	70.1	0.7
9 2-methyl-1-butene	0.00	70.1	0.67
10 2-methyl-1,3-butadiene	0.00	68.1	0.65

1.00000 = Sum of Mass Fractions

How Do I Measure a Distribution?

Return to Critical Volume Prod.

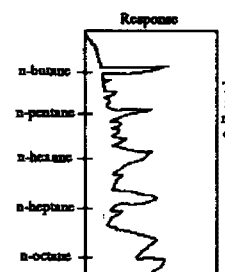
Print List

SD11

How Do I Measure a Distribution?

Determining the exact composition of complex mixtures (such as gasoline) requires specialized analytical techniques. For the purpose of estimating the response to venting, however, an approximate composition can be used with very good results.

To determine an approximate distribution, one must analyze the mixture by gas chromatographic analyses. Prior to the analyses, choose about 6 - 10 marker compounds whose properties are well known.



SD12

Calculate a Distribution

Calculate a Distribution

1 Perform a GC analysis and sum all peaks whose retention times lie between the known compounds.

2 Enter the areas or concentrations in the appropriate location in the Table on the right. Then, Click Calculate.

3 Click the "Transfer Data..." button and your distribution will be copied to the Composition Table.

#	Compound	Concentration or Area	Normalized Distribution
1	propane	0.00	0.00000
2	n-butane	0.00	0.00000
3	n-pentane	0.00	0.00000
4	n-hexane	1111	1.00000
5	n-heptane	0.00	0.00000
6	n-octane	0.00	0.00000
7	n-nonane	0.00	0.00000
8	n-decane	0.00	0.00000
9	n-undecane	0.00	0.00000
10	n-dodecane	0.00	0.00000

(Reset) Calculate

SD13

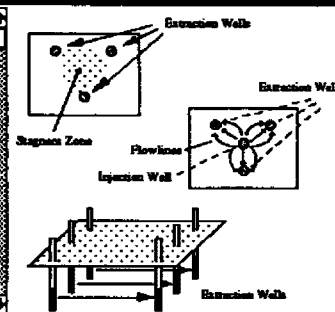
Return

Transfer Data to Distribution Card

Well Location

To be able to successfully locate extraction wells, passive wells, and surface seals one must have a good understanding of vapor flow behavior. Wells locations should be chosen to maximize vapor flow through the contaminated zone, while minimizing vapor flow through other zones.

If one well is sufficient, it should almost always be placed in the geometric center of the



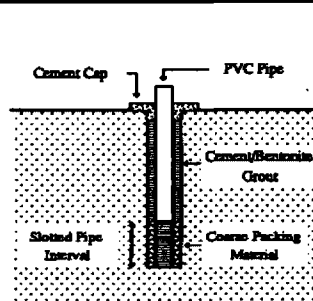
SD14

Return to Design

Well Construction

Wells should be screened only through the zone of contamination, unless the permeability to vapor flow is so low that removal rates would be greater if flow were induced in an adjacent soil layer. Removal rate estimates for various mass-transfer limited scenarios are discussed elsewhere in this stack.

Based on predictive equations, the flowrate is expected to increase by 15% when the extraction well

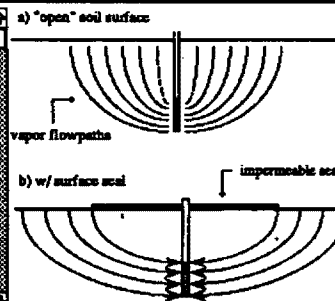


SD15

Return to Design

Surface Seals

Surface seals, such as polymer-based liners and asphalt, concrete, or clay caps, are sometimes used to control the vapor flow paths. Figure 12 illustrates the effect that a surface seal will have on vapor flow patterns. For shallow treatment zones (<5 m) the surface seal will have a significant effect on the vapor flow paths, and seals can be added or removed to achieve the desired vapor flowpath. For

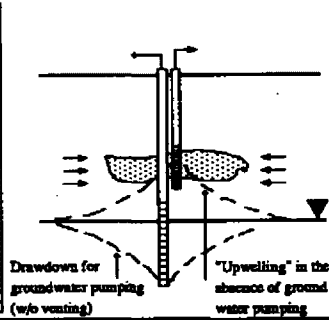


SD16

Return to Design

Groundwater Pumping Systems

In cases where contaminated soils lie just above or below the water table, groundwater pumping systems will be required to insure that contaminated soils remain exposed. In designing a groundwater system it is important to be aware that upwelling (draw-up) of the groundwater table will occur when a vacuum is applied at the extraction well (see the figure at the right).



SD17

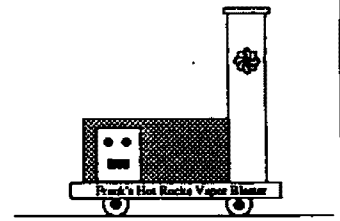
Return to Design

Vapor Treatment Systems

Currently there are four main treatment processes available:

VAPOR COMBUSTION UNITS:

Vapors are incinerated and destruction efficiencies are typically >95%. A supplemental fuel, such as propane, is added before combustion unless extraction well vapor concentrations are on the order of



SD18

Return to Design

Appendix F: "Compound List Update" stack cards.

Compound List Update

This card is provided as a utility to let you add, or delete compounds from the Compound List Data Base that this program uses. You may not delete or change the properties of the base 62 compounds, since these are needed for the two default gasoline case calculations (i.e. the "Fresh" and "Weathered" gasolines). If you wish to change any of the properties of the added chemicals, first delete them, then reinsert them into the Compound List Data Base. Follow the directions below:

1 Choose one of the following:

☒ insert chemical

☐ delete chemical

2 Input the parameters at the right

(use lowercase compound

name for consistency)

3 click on the button to the right

(use only 30 characters or less)

Chemical Name:

Molecular Weight [g/mole]

Vapor Pressure @20C [atm]

Boiling Point @1 atm [C]

Exponential Notation Not Accepted!



CLI

Appendix G: Reprint of:

***"A Practical Approach to the Design, Operation, and
Monitoring of In Situ Soil Venting Systems"***

A Practical Approach to the Design, Operation, and Monitoring of In Situ Soil-Venting Systems

by P.C. Johnson, C.C. Stanley, M.W. Kemblowski, D.L. Byers, and J.D. Colthart

Abstract

When operated properly, in situ soil venting or vapor extraction can be one of the most cost-effective remediation processes for soils contaminated with gasoline, solvents, or other relatively volatile compounds. The components of soil-venting systems are typically off-the-shelf items, and the installation of wells and trenches can be done by reputable environmental firms. However, the design, operation, and monitoring of soil-venting systems are not trivial. In fact, choosing whether or not venting should be applied at a given site is a difficult decision in itself. If one decides to utilize venting, design criteria involving the number of wells, well spacing, well location, well construction, and vapor treatment systems must be addressed. A series of questions must be addressed to decide if venting is appropriate at a given site and to design cost-effective in situ soil-venting systems. This series of steps and questions forms a "decision tree" process. The development of this approach is an attempt to identify the limitations of in situ soil venting, and subjects or behavior that are currently difficult to quantify and for which future study is needed.

Introduction

When operated properly, in situ soil venting or vapor extraction can be a cost-effective remediation process for soils contaminated with gasoline, solvents, or other relatively volatile compounds. A "basic" system, such as the one shown in Figure 1, couples vapor extraction (recovery) wells with blowers or vacuum pumps to remove vapors from the vadose zone and thereby reduce residual levels of soil contaminants. More complex systems incorporate trenches, air injection wells, passive wells, and surface seals. Above-ground treatment systems condense, adsorb, or incinerate vapors; in some cases vapors are simply emitted to the atmosphere through diffuser stacks. In situ soil venting is an especially attractive treatment option because the soil is treated in place, sophisticated equipment is not required, and the cost is typically lower than other options.

The basic phenomena governing the performance of soil-venting systems are easily understood. By applying a vacuum and removing vapors from extraction wells, vapor flow through the unsaturated soil zone is induced. Contaminants volatilize from the soil matrix and are swept by the carrier gas flow (primarily air) to the extraction wells or trenches. Many complex processes occur on the microscale, however, the three main factors that control the performance of a venting operation are the chemical composition of the contaminant, vapor flow rates through the unsaturated zone, and the flow path of carrier vapors relative to the location of the contaminants.

The components of soil-venting systems are typically

off-the-shelf items, and the installation of wells and trenches can be done by reputable environmental firms. However, the design, operation, and monitoring of soil-venting systems is not trivial. In fact, choosing whether or not venting should be applied at a given site is a difficult question in itself. If one decides to utilize venting, design criteria involving the number of wells, well spacing, well location, well construction, and vapor treatment systems must be addressed. It is the current state-of-the-art that such questions are answered more by experience than by rigorous logic. This is evidenced by published soil venting "success stories" (see Hutzler et al. 1988 for a good review), which rarely include insight into the design process.

In this paper, a series of questions are presented that must be addressed to:

- Decide if venting is appropriate at a given site.
- Design cost-effective in situ soil-venting systems.

This series of steps and questions forms a "decision tree" process. The development of this approach is an attempt to identify the limitations of in situ soil venting, and subjects or behavior that are currently difficult to quantify and for which future study is needed.

The "Practical Approach"

Figure 2 presents a flow chart of the process discussed in this paper. Each step of the flow chart will be discussed in detail, and where appropriate, examples are given.

The Site Characterization

Whenever a soil contamination problem is detected or suspected, a site investigation is conducted to charac-

terize and delineate the zone of soil and ground water contamination. In general, the site characterization is conducted in two stages. The emergency response and abatement phase assesses the immediate impact on potential human and environmental receptors, and is conducted in a relatively short period of time (days). A detailed site characterization then follows. Its purpose, like the emergency response and abatement phase, is to determine potential migration pathways and assess the environmental impact associated with present conditions and future migration of the contaminants. Often the sequence of steps following initial response and abatement is as follows:

- **Background review:** Involves assembling historical records, plot plans, engineering drawings (showing utility lines), and interviewing site personnel. This information is used to help identify the contaminant, probable source of release, zone of contamination, and potentially impacted areas (neighbors, drinking water supplies, etc.).
- **Preliminary site screening:** Preliminary screening tools such as soil-gas surveys and cone penetrometers are used to roughly define the zone of contamination and the site geology. Knowledge of site geology is essential to determine probable migration of contaminants through the unsaturated zone.
- **Detailed site characterization:** Soil borings are drilled and monitoring wells are installed.
- **Contaminant characterization:** Soil and ground water samples are analyzed to determine contaminant concentrations and compositions.

Costs associated with site investigations can be relatively high depending on the complexity of the site and size of the spill or leak. For large spills and complex site geological/hydrogeological conditions, site investigation costs may begin to approach remediation costs. In addition, the choice and design of a remediation system is based on the data obtained during the site investigation. For these reasons it is important to ensure that specific information is collected, and to validate the quality of the data.

If it is presumed that in situ soil venting will be a candidate for treatment, then the following information needs to be obtained during the preliminary site investigation:

- **Subsurface characteristics — site geology:** This includes the determination of soil stratigraphy (vadose and saturated zone) and characteristics of distinct soil layers (i.e., soil type, permeability estimates). While they are not essential, the moisture content, total organic carbon, and permeability of each distinct soil layer also provides useful information that can be used to choose and design a remediation system.
- **Subsurface characteristics — site hydrogeology:** Depth to ground water, and the ground water gradient must be known, as well as estimates of the aquifer hydraulic conductivity.
- **Contaminant delineation:** The distribution of contaminants in the saturated and vadose zones needs to be assessed. This includes the extent of the free-phase hydrocarbon, residual hydrocarbon, and solu-

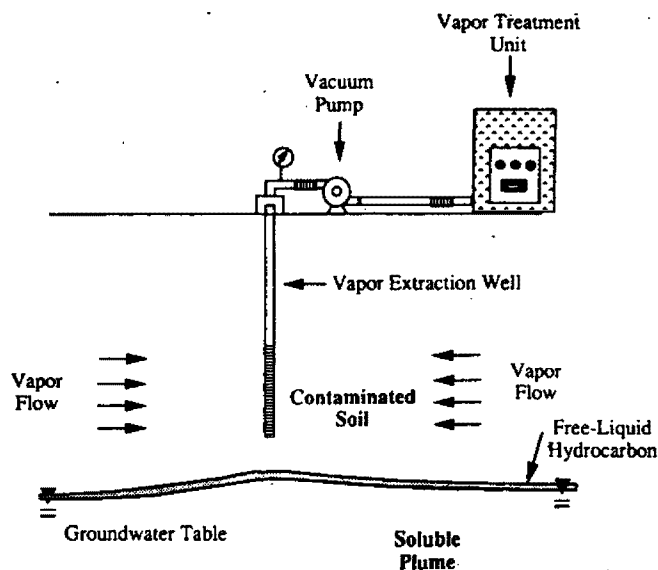


Figure 1. "Basic" in situ soil-venting system.

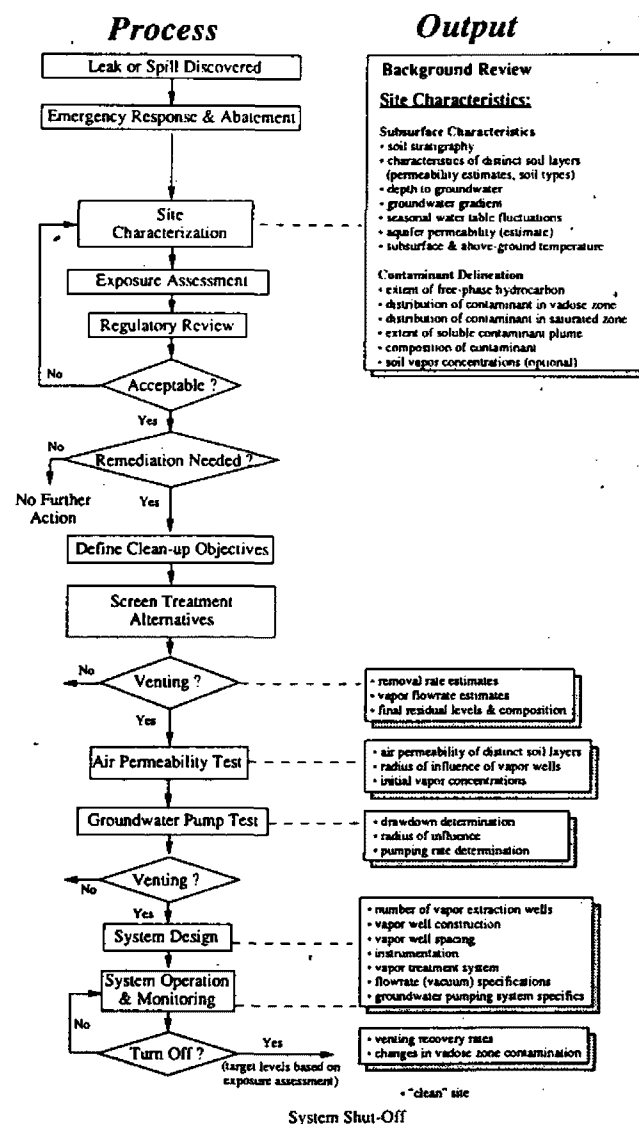


Figure 2. In situ soil-venting system design process.

ble hydrocarbon. Soil samples should be analyzed to determine which contaminants are present at what levels (contaminant composition). Specific analytical methods should be used to identify target compounds (i.e., benzene, toluene, or xylenes) and total hydrocarbons present. For soil analyses these methods are:

EPA 8240, 8020, 8010 - volatile organic chemicals (VOCs)

EPA 8270 - semivolatile organic chemicals

EPA 418.1 - total petroleum hydrocarbons (TPH).

The corresponding methods for water samples are:

EPA 8240, 8020, 8010 - volatile organic chemicals (VOCs)

EPA 8270 - semivolatile organic chemicals

EPA 418.1 - total petroleum hydrocarbons (TPH).

With the current high cost of chemical analyses it is important to intelligently select which analyses should be performed and which samples should be sent to a certified laboratory. Local regulations usually require that a minimum number of soil borings be performed, and target compounds must be analyzed based on the suspected composition of the contamination. Costs can be minimized and more data obtained by utilizing field screening tools, such as hand-held vapor meters or portable field gas chromatographs (GCs). These instruments can be used to measure both residual soil contamination levels and headspace vapors above contaminated soils. At a minimum, soil samples corresponding to lithology changes or obvious changes in residual levels (based on visual observations or odor) should be analyzed.

For complex contamination mixtures, such as gasoline, diesel fuel, and solvent mixtures, it is not practical or necessary to identify and quantify each compound present. In such cases it is recommended that a "boiling point" distribution be measured for a representative sample of the residual contamination. Boiling point distribution curves, such as shown in Figure 3 for "fresh" and "weathered" gasoline samples, can be constructed from GC analyses of the residual soil contamination (or free product) and knowledge of the GC elution behavior of a known series of compounds (such as straight-chain alkanes). Compounds generally elute from a GC packed column in the order of increasing boiling point, so a boiling point distribution curve is constructed by grouping all unknowns that elute between two known peaks (i.e., between n-hexane and n-heptane). Then they are assigned an average boiling point, molecular weight, and vapor pressure. Use of these data will be explained later.

The cone penetrometer, which is essentially an instrumented steel rod that is driven into the soil, is becoming a popular tool for preliminary site screening investigations. By measuring the shear and normal forces on the leading end of the rod, soil structure can be defined and permeability or hydraulic conductivity can be estimated. Some cone penetrometers are also constructed to allow the collection of vapor or ground water samples. This tool has several advan-

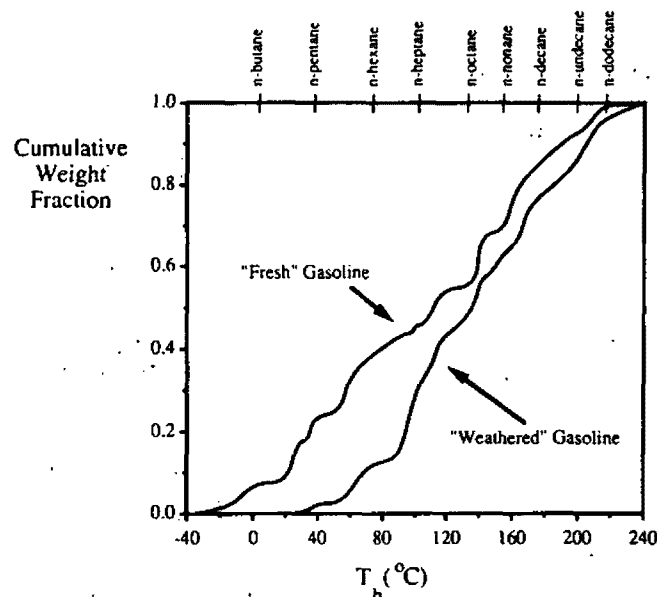


Figure 3. Boiling point distribution curves for samples of "fresh" and "weathered" gasolines.

tages over conventional soil boring techniques (as a preliminary site characterization tool): (1) the subsurface soil structure can be defined better; (2) no soil cuttings are generated; and (3) more analyses can be performed per day.

- **Temperature** (both above and below ground surface) Contaminant vapor concentrations are dependent on temperature, and therefore, removal rates are strongly influenced by subsurface temperatures. Above-ground temperatures will influence the selection of materials and construction of the above-ground vapor treatment system.

Results from the preliminary site investigation should be summarized in contour plots, fence diagrams, and tables in preparation for deciding whether venting is appropriate, and for the final design of the system.

Deciding if Venting Is Appropriate

As previously stated, the three main factors governing the behavior of any in situ soil-venting operation are the vapor flow rate, contaminant vapor concentrations, and the vapor flow path relative to the contaminant location. In an article by Johnson et al. (1988), simple mathematical equations were presented to help quantify each of these factors. Following it is illustrated how to use these "screening models" and the information collected during the preliminary site investigation to help determine if in situ soil venting is appropriate at a given site. In making this decision the following questions will be answered:

1. What contaminant vapor concentrations are likely to be obtained?
2. Under ideal vapor flow conditions (i.e., 100 - 1000 scfm vapor flow rates), is this concentration great enough to yield acceptable removal rates?
3. What range of vapor flow rates can realistically be achieved?
4. Will the contaminant concentrations and realistic vapor flow rates produce acceptable removal rates?
5. What residual, if any, will be left in the soil? What

vapor composition and concentration changes will occur with time? How do these values relate to the regulatory requirements?

6. Are there likely to be any negative effects of soil venting?

Negative answers to questions 2 or 4 will rule out in situ soil venting as a practical treatment method.

What Contaminant Vapor Concentrations Are Likely to Be Obtained?

Question 1 can be answered based on the results of soil-vapor surveys, analyses of headspace vapors above contaminated soil samples, or equilibrium vapor models (Johnson et al. 1988). In some cases just knowing which compounds are present is sufficient to estimate if venting is feasible. In the absence of soil-vapor survey data, contaminant vapor concentrations can be estimated. The maximum vapor concentration of any compound (mixture) in extracted vapors is its equilibrium or "satur-

ated" vapor concentration, which is easily calculated from knowledge of the compound's (mixture's) molecular weight, vapor pressure at the soil temperature, residual soil contaminant composition, and the ideal gas law:

$$C_{\text{est}} = \sum_i \frac{x_i P_i^* M_{w,i}}{RT} \quad (1)$$

where:

C_{est} = estimate of contaminant vapor concentration [mg/L]

x_i = mole fraction of component i in liquid-phase residual ($x_i = 1$ for single compound)

P_i^* = pure component vapor pressure at temperature T [atm]

$M_{w,i}$ = molecular weight of component i [mg/mole]

R = gas constant = 0.0821 l-atm/mole-°K

T = absolute temperature of residual [°K].

Table 1 presents data for some chemicals and mix-

TABLE 1
Selected Compounds and Their Chemical Properties (Johnson et al. 1988)

Compound	M_w (g/mole)	T_b (1 atm) (C)	P_v^* 20 C (atm)	C_{est} (mg/L)
n-pentane	72.2	36	0.57	1700
n-hexane	86.2	69	0.16	560
trichloroethane	133.4	75	0.132	720
benzene	78.1	80	0.10	320
cyclohexane	84.2	81	0.10	340
trichloroethylene	131.5	87	0.026	140
n-heptane	100.2	98	0.046	190
toluene	92.1	111	0.029	110
tetrachloroethylene	166	121	0.018	130
n-octane	114.2	126	0.014	65
chlorobenzene	113	132	0.012	55
p-xylene	106.2	138	0.0086	37
ethylbenzene	106.2	138	0.0092	40
m-xylene	106.2	139	0.0080	35
o-xylene	106.2	144	0.0066	29
styrene	104.1	145	0.0066	28
n-nonane	128.3	151	0.0042	22.0
n-propylbenzene	120.2	159	0.0033	16
1,2,4 trimethylbenzene	120.2	169	0.0019	9.3
n-decane	142.3	173	0.0013	7.6
DBCP	263	196	0.0011	11
n-undecane	156.3	196	0.0006	3.8
n-dodecane	170.3	216	0.00015	1.1
naphthalene	128.2	218	0.00014	0.73
tetraethyllead	323	dec.@200C	0.0002	2.6
gasoline ¹	95	-	0.34	1300
weathered gasoline ²	111	-	0.049	220

¹Corresponds to "fresh" gasoline defined in Table 2 with boiling point distribution shown in Figure 3.

²Corresponds to "weathered" gasoline defined in Table 2 with boiling point distribution shown in Figure 3.

T_b (1 atm) - compound boiling point at 1 atm absolute pressure.

M_w - molecular weight.

C_{est} - equilibrium vapor concentration (see Equation 1).

P_v^* (20 C) - vapor pressure measured at 20 C.

tures accidentally released to the environment. There are more sophisticated equations for predicting vapor concentrations in soil systems based on equilibrium partitioning arguments, but these require more detailed information (organic carbon content, soil moisture) than is normally available. If a site is chosen for remediation, the residual total hydrocarbons in soil typically exceed 500 mg/kg. In this residual concentration range most of the hydrocarbons will be present as a separate or "free" phase, the contaminant vapor concentrations become independent of residual concentration (but still depend on composition), and Equation 1 is applicable (Johnson et al. 1988). In any case, it should be noted that these are estimates only for vapor concentrations at the start of venting, which is when the removal rates are generally greatest. Contaminant concentrations in the extracted vapors will decline with time due to changes in composition, residual levels, or increased diffusional resistances. These topics will be discussed in more detail.

Under Ideal Vapor Flow Conditions (i.e., 100 – 1000 scfm Vapor Flow Rates), Is This Concentration Great Enough to Yield Acceptable Removal Rates?

Question 2 is answered by multiplying the concentration estimate C_{est} , by a range of reasonable flow rates, Q :

$$R_{est} = C_{est} Q \quad (2)$$

Here R_{est} denotes the estimated removal rate, and C_{est} and Q must be expressed in consistent units. For reference, documented venting operations at service station sites typically report vapor flow rates in the 10 – 100 scfm range (Hutzler et al. 1988), although 100 – 1000 scfm flow rates are achievable for sandy soils or large numbers of extraction wells. At this point in the decision process what is still being neglected is that vapor concentrations decrease during venting due to compositional changes and mass transfer resistances. Figure 4 presents calculated removal rates R_{est} [kg/d] for a range of C_{est} and Q values. C_{est} values are presented in [mg/L] and [ppm_{CH₄}] units, where [ppm_{CH₄}] represents methane-equivalent parts-per-million volume/volume (ppm_v) units. The [ppm_{CH₄}] units are used because field analytical tools that report [ppm_v] values are often calibrated with methane. The [mg/L] and [ppm_{CH₄}] units are related by:

$$[mg/L] = \frac{[ppm_{CH_4}] \cdot 16000 \text{ mg-CH}_4/\text{mole-CH}_4 \cdot 10^{-6}}{(0.0821 \text{ l-atm}^\circ\text{K-mole}) \cdot (298 \text{ K})} \quad (3)$$

For field instruments calibrated with other compounds (i.e., butane, propane), [ppm_v] values are converted to [mg/L] by replacing the molecular weight of CH₄ in Equation 3 by the molecular weight [mg/mole] of the calibration compound.

Acceptable or desirable removal rates $R_{acceptable}$, can be determined by dividing the estimated spill mass M_{spill} , by the maximum acceptable cleanup time τ :

$$R_{acceptable} = M_{spill}/\tau \quad (4)$$

For example, if 1500kg (\approx 500 gal) of gasoline had been spilled at a service station and it was wished to

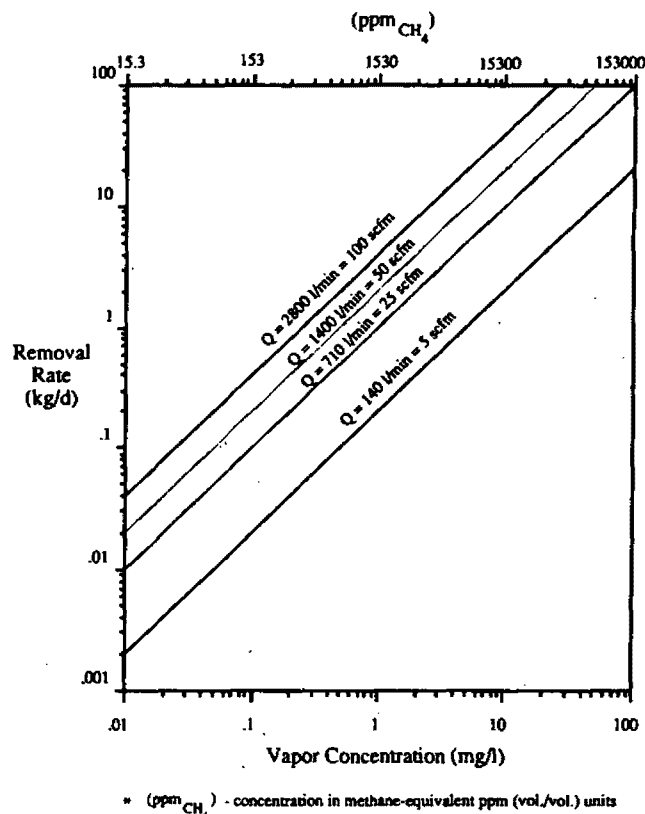


Figure 4. In situ soil-venting removal rate dependence on vapor extraction rate and vapor concentration.

complete the cleanup within eight months, then $R_{acceptable} = 6.3$ kg/d. Based on Figure 4, therefore, C_{est} would have to average >1.5 mg/L (2400 ppm_{CH₄}) for $Q=2800$ l/min (100 scfm) if venting is to be an acceptable option. Generally, removal rates <1 kg/d will be unacceptable for most releases, so soils contaminated with compounds (mixtures) having saturated vapor concentrations less than 0.3 mg/L (450 ppm_{CH₄}) will not be good candidates for venting, unless vapor flow rates exceed 100 scfm. Judging from the compounds listed in Table 1, this corresponds to compounds with boiling points (T_b) >150 °C, or pure component vapor pressures <0.0001 atm evaluated at the subsurface temperature.

What Range of Vapor Flow Rates Can Realistically Be Achieved?

Question 3 requires that realistic vapor flow rates for the site-specific conditions be estimated. Equation 5, which predicts the flow rate per unit thickness of well screen Q/H [cm³/s], can be used for this purpose:

$$\frac{Q}{H} = \pi \frac{k}{\mu} p_w \frac{[1 - (P_{Atm}/P_w)^2]}{\ln(R_w/R_l)} \quad (5)$$

where:

k = soil permeability to air flow [cm²] or [darcy]

μ = viscosity of air = 1.8×10^{-4} g/cm-s or 0.018 cp

P_w = absolute pressure at extraction well [g/cm-s²] or [atm]

P_{Atm} = absolute ambient pressure $\approx 1.01 \times 10^6$ g/cm-s² or 1 atm

R_w = radius of vapor extraction well [cm]

R_l = radius of influence of vapor extraction well [cm].

This equation is derived from the simplistic steady-state radial flow solution for compressible flow (Johnson et al. 1988), but should provide reasonable estimates for vapor flow rates. If k can be measured or estimated, then the only unknown parameter is the empirical "radius of influence" R_I . Values ranging from 9m (30 ft) to 30m (100 ft) are reported in the literature (Hutzler et al. 1988) for a variety of soil conditions, but fortunately Equation 5 is not sensitive to large changes in R_I . For estimation purposes, therefore, a value of $R_I=12\text{m}$ (40 ft) can be used without a significant loss of accuracy. Typical vacuum well pressures range from 0.95 - 0.90 atm (20 - 40 in H_2O vacuum). Figure 5 presents predicted flow rates per unit well screen thickness Q/H , expressed in "standard" volumetric units Q^*/H ($= Q/H(P_w/P_{\text{atm}})$) for a 5.1cm radius (4-in diameter) extraction well, and a wide range of soil permeabilities and applied vacuums. Here H denotes the thickness of the screened interval, which is often chosen to be equal to the thickness of the zone of soil contamination (this minimizes removing and treating any excess "clean" air). For other conditions the Q^*/H values in Figure 5 can be multiplied by the following factors:

$R_w = 5.1\text{cm}$ (2 in) $R_I = 7.6\text{m}$ (25 ft) - multiply Q^*/H by 1.09
 $R_w = 5.1\text{cm}$ (2 in) $R_I = 23\text{m}$ (75 ft) - multiply Q^*/H by 0.90
 $R_w = 7.6\text{cm}$ (3 in) $R_I = 12\text{m}$ (40 ft) - multiply Q^*/H by 1.08
 $R_w = 10\text{cm}$ (4 in) $R_I = 12\text{m}$ (40 ft) - multiply Q^*/H by 1.15
 $R_w = 10\text{cm}$ (4 in) $R_I = 7.6\text{m}$ (25 ft) - multiply Q^*/H by 1.27

As indicated by the preceding multipliers given, changing the radius of influence from 12m (40 ft) to 23 m (75 ft) only decreases the predicted flow rate by 10 percent. The largest uncertainty in flow rate calculations will be due to the air permeability value k , which can vary by one to three orders of magnitude across a site and can realistically only be estimated from boring log data within an order of magnitude. It is prudent, therefore, to choose a range of k values during this phase of the decision process. For example, if boring logs indicate fine sandy soils are present, then flow rates should be calculated for k values in the range of $0.1 < k < 1.0$ darcy.

Will the Contaminant Concentrations and Realistic Vapor Flow Rates Produce Acceptable Removal Rates?

Again, estimated removal rates R_{est} , must be compared with an acceptable rate $R_{\text{acceptable}}$, as determined from Equation 4. Maximum removal rates are achieved when the induced vapor flow travels only through the zone of soil contamination and no mass-transfer limitations are encountered. In other words, all vapor flows through contaminated soils and becomes saturated with contaminant vapors. For this "best" case the estimated removal rate is given by Equation 2:

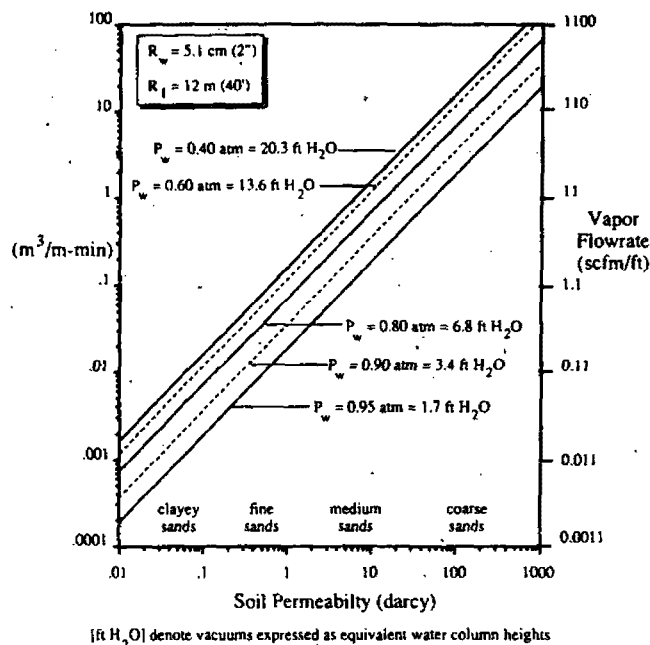


Figure 5. Predicted steady-state flow rates (per unit well screen thickness) for a range of soil permeabilities and applied vacuums (P_w).

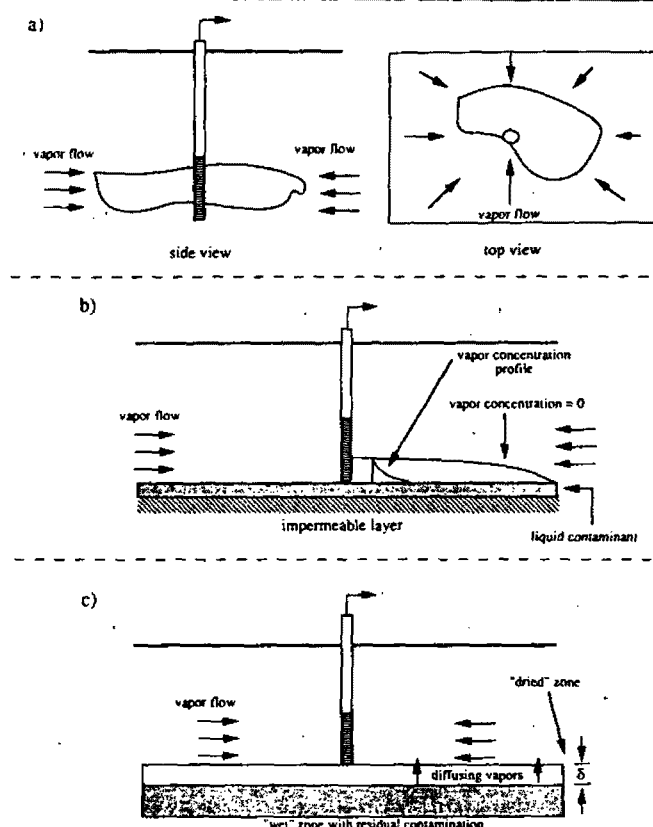


Figure 6. Scenarios for removal rate estimates.

$$R_{\text{est}} = C_{\text{est}} Q \quad (2)$$

Changes in C_{est} are still being neglected with time due to composition changes. Other less optimal conditions are often encountered in practice and it is useful to be able to quantify how much lower the removal rate will be from the value predicted by Equation 2. We will consider the three cases illustrated in Figures 6a, b, and c.

In Figure 6a a fraction ϕ of the vapor flows through uncontaminated soil. The fraction can be roughly estimated by assessing the location of the well relative to the contaminant distribution. In Figure 6a for example, it appears that roughly 25 percent of the vapor flows through uncontaminated soil. The maximum removal rate for this case is then:

$$R_{est} = (1 - \phi) Q C_{est} \quad (6)$$

In Figure 6b, vapor flows parallel to, but not through, the zone of contamination, and the significant mass transfer resistance is vapor phase diffusion. This would be the case for a layer of liquid hydrocarbon resting on top of an impermeable strata or the water table. This problem was studied by Johnson et al (1988) for the case of a single component. The solution is:

$$R_{est} = \eta Q C_{est}$$

$$\eta = \frac{1}{3H} (6D\mu/k)^{1/2} [\ln(R_1/R_w) / (P_{Atm} - P_w)]^{1/2} \sqrt{R_2^2 - R_1^2} \quad (7)$$

where:

- η = efficiency relative to maximum removal rate
- D = effective soil-vapor diffusion coefficient [cm^2/s]
- μ = viscosity of air = 1.8×10^{-4} g/cm-s
- k = soil permeability to vapor flow [cm^2]
- H = thickness of screened interval [cm]
- R_1 = radius of influence of venting well [cm]
- R_w = venting well radius [cm]
- P_{Atm} = absolute ambient pressure = 1.016×10^6 g/cm-s²
- P_w = absolute pressure at the venting well [g/cm-s^2]
- $R_1 < r < R_2$ = defines region in which contamination is present.

Note that the efficiency η is inversely proportional to the screened interval thickness H because a larger interval will, in this geometry, pull in unsaturated air that has passed above the liquid-phase contamination. D is calculated by the Millington-Quirk (Millington and Quirk 1961) expression, which utilizes the molecular diffusion coefficient in air D^0 , the vapor-filled soil porosity ϵ_A , and the total soil porosity ϵ_T :

$$D = D^0 \frac{\epsilon_A^{3.33}}{\epsilon_T^2} \quad (8)$$

where ϵ_A and ϵ_A are related by:

$$\epsilon_A = \epsilon_T - \rho_b \theta_M \quad (9)$$

Here ρ_b and θ_M are the soil bulk density [g/cm^3] and soil moisture content [$\text{g-H}_2\text{O/g-soil}$].

As an example, consider removing a layer of contamination bounded by sandy soil ($k=1$ darcy). A 5.1cm (4 in) radius vapor extraction well is being operated at $P_w=0.90$ atm (0.91×10^6 g/cm-s²), and the contamination extends from the region $R_1 = R_w = 5.1\text{cm}$ to $R_2 = 9\text{m}$ (30 ft). The well is screened over a 3m (10 ft) interval.

Assuming that:

$$\begin{aligned} \rho_b &= 1.6 \text{ g/cm}^3 \\ \theta_M &= 0.10 \\ D^0 &= 0.087 \text{ cm}^2/\text{s} \\ \epsilon_T &= 0.30 \\ R_1 &= 12 \text{ m} \end{aligned}$$

then the venting efficiency relative to the maximum removal rate (Equation 2), calculated from Equations 7 through 9 is:

$$\eta = 0.09 = 9\%$$

Figure 6c depicts the situation in which vapor flows primarily past, rather than through the contaminated soil zone, such as might be the case for a contaminated clay lens surrounded by sandy soils. In this case vapor-phase diffusion through the clay to the flowing vapor limits the removal rate. The maximum removal rate in this case occurs when the vapor flow is fast enough to maintain a low vapor concentration at the permeable/impermeable soil interface. At any time t a contaminant-free or "dried out" zone of low permeability will exist with a thickness δ . An estimate of the removal rate R_{est} from a contaminated zone extending from R_1 to R_2 is:

$$R_{est} = \pi (R_2^2 - R_1^2) C_{est} D / \delta(t) \quad (10)$$

where D is the effective porous media vapor diffusion coefficient (as calculated previously from Equations 8 and 9) and C_{est} is the estimated equilibrium vapor concentration (Equation 1). With time $\delta(t)$ will grow larger. In the case of a single component system the dry zone thickness can be calculated from the mass balance:

$$\rho_b C_s \frac{d\delta}{dt} = C_{est} D / \delta(t) \quad (11)$$

$$R_{est} = \pi (R_2^2 - R_1^2) \sqrt{\frac{C_{est} D C_s \rho_b}{2t}}$$

where C_s is the residual level of contamination in the low permeability zone [$\text{g-contamination/g-soil}$], and all other variables have been defined. The solution to Equations 10 and 11 yields the following equation that predicts the change in removal rate with time:

$$\delta(t) = \sqrt{\frac{2 C_{est} D t}{\rho_b C_s}} \quad (12)$$

As an example, consider the case where benzene ($C_v = 3.19 \times 10^{-4}$ g/cm³ @20 C) is being removed from a zone extending from $R_1 = 5.1\text{cm}$ to $R_2 = 9\text{m}$. The initial residual level is 10,000 ppm (0.01 g-benzene/g-soil), $\rho_b = 1.6 \text{ g/cm}^3$, $D^0 = 0.087 \text{ cm}^2/\text{s}$, and $\epsilon_T = \epsilon_A = 0.30$. Figure 7 presents the predicted removal rates and "dry" zone thickness $\delta(t)$ as a function of time. Note that it would take approximately one year to clean a layer 1.5m (5 ft) thick, for a compound as volatile as benzene. Equation 12 predicts high initial removal rates; in practice, however, the removal rate will be limited initially by the vapor-phase diffusion behavior described previously for Figure 6b.

Mixture removal rates for the situations depicted in Figures 6b and 6c are difficult to estimate because

changes in composition and liquid-phase diffusion affect the behavior. Currently there are no simple analytical solutions for these situations, but it can be postulated that they should be less than the rates predicted previously for pure components.

The use of equilibrium-based models to predict required removal rates will be discussed under the next question.

What Residual, If Any, Will Be Left in the Soil? What Vapor Composition and Concentration Changes Will Occur With Time? How Do These Values Relate to the Regulatory Requirements?

As contaminants are removed during venting, the residual soil contamination level decreases and mixture compositions become richer in the less volatile compounds. Both of these processes result in decreased vapor concentrations, and hence, decreased removal rates with time. At low residual soil contamination levels (<500 ppm) Equation 1 becomes less valid as sorption and dissolution phenomena begin to affect the soil residual - vapor equilibrium. In the limit of low residual contamination levels, contaminant equilibrium vapor concentrations are expected to become proportional to the residual soil contaminant concentrations. As venting continues and residual soil levels decrease, therefore, it becomes more difficult to remove the residual contamination. It is important to realize that, even with soil venting, there are practical limitations on the final soil contamination levels that can be achieved. Knowledge of these limits is necessary to realistically set cleanup criteria and design effective venting systems.

The maximum efficiency of a venting operation is limited by the equilibrium partitioning of contaminants between the soil matrix and vapor phases. The maximum removal rate is achieved when the vapor being removed from an extraction well is in equilibrium with the contaminated soil. Models for predicting this maximum removal rate have been presented by Marley and Hoag (1984) and Johnson et al. (1988). The former considered only compositions in a residual free-phase, while the latter also considered the effects of sorption and dissolution processes. A complete discussion of the development of these models is not appropriate here, but we will discuss the use of the predictions.

The change in composition, vapor concentration, removal rate, and residual soil contamination level with time are functions of the initial residual composition, vapor extraction well flow rate, and initial soil contamination level. It is not necessary to generate predictions for every combination of variables, however, because with appropriate scaling all results will form a single curve for a given initial mixture composition. Figure 8a presents the results computed with the model presented by Johnson et al. (1988) for the "weathered" gasoline mixture whose composition is given by Table 2. The important variable that determines residual soil levels, vapor concentrations, and removal rates is the ratio $Q_t/M(t=0)$, which represents the volume of air drawn through the contaminated zone per unit mass of con-

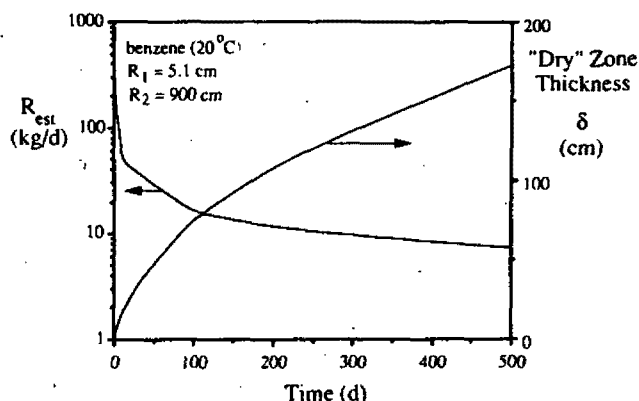


Figure 7. Estimated maximum removal rates for a venting operation limited by diffusion.

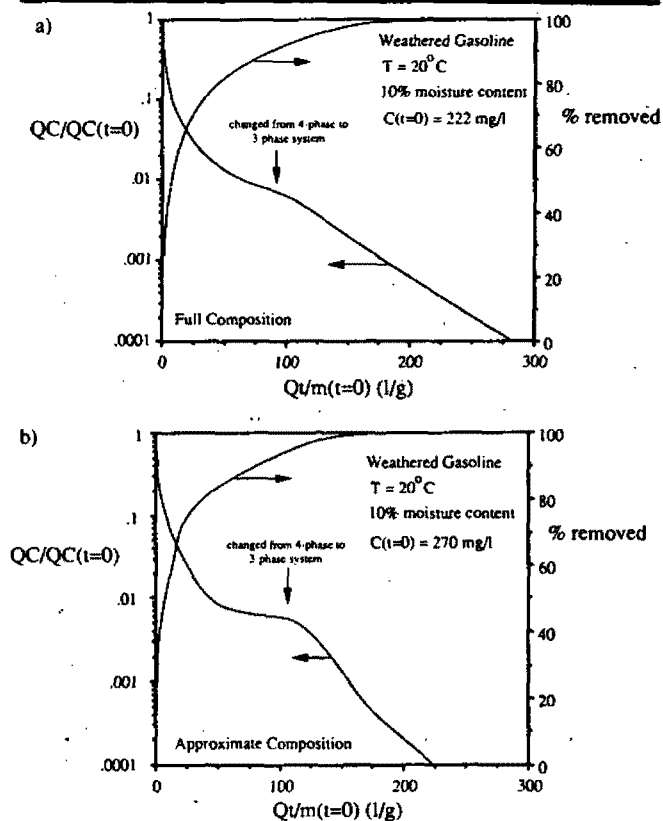


Figure 8. Maximum predicted removal rates for a weathered gasoline: (a) full composition (b) approximate composition.

minant. In Figure 8, the scaled removal rate (or equivalently the vapor concentration) decreases with time as the mixture becomes richer in the less volatile compounds.

While a detailed compositional analysis was available for this gasoline sample, an approximate composition based on a boiling point distribution curve predicts similar results. Figure 8b presents the results for the approximate mixture composition also given in Table 2.

Model predictions, such as those shown in Figure 8 for the gasoline sample defined by Table 2, can be used to estimate removal rates (if the vapor flow rate is specified), or alternatively the predictions can be used to estimate vapor flow rate requirements (if the desired removal rate is specified). For example, if we wanted to reduce the initial contamination level by 90 percent,

TABLE 2
Composition (Mass Fractions) of Fresh and Weathered Gasolines

Compound Name	M _w (g)	Fresh Gasoline	Weathered Gasoline	Approximate Composition
propane	44.1	0.0001	0.0000	0
isobutane	58.1	0.0122	0.0000	0
n-butane	58.1	0.0629	0.0000	0
trans-2-butene	56.1	0.0007	0.0000	0
cis-2-butene	56.1	0.0000	0.0000	0
3-methyl-1-butene	70.1	0.0006	0.0000	0
isopentane	72.2	0.1049	0.0069	0.0177
1-pentene	70.1	0.0000	0.0005	0
2-methyl-1-butene	70.1	0.0000	0.0008	0
2-methyl-1,3-butadiene	68.1	0.0000	0.0000	0
n-pentane	72.2	0.0586	0.0095	0
trans-2-pentene	70.1	0.0000	0.0017	0
2-methyl-2-butene	70.1	0.0044	0.0021	0
2-methyl-1,2-butadiene	68.1	0.0000	0.0010	0
3,3-dimethyl-1-butene	84.2	0.0049	0.0000	0
cyclopentane	70.1	0.0000	0.0046	0.0738
3-methyl-1-pentene	84.2	0.0000	0.0000	0
2,3-dimethylbutane	86.2	0.0730	0.0044	0
2-methylpentane	86.2	0.0273	0.0207	0
3-methylpentane	86.2	0.0000	0.0186	0
n-hexane	86.2	0.0283	0.0207	0
methylcyclopentane	84.2	0.0083	0.0234	0
2,2-dimethylpentane	100.2	0.0076	0.0064	0
benzene	78.1	0.0076	0.0021	0
cyclohexane	84.2	0.0000	0.0137	0.1761
2,3-dimethylpentane	100.2	0.0390	0.0000	0
3-methylhexane	100.2	0.0000	0.0355	0
3-ethylpentane	100.2	0.0000	0.0000	0
n-heptane	100.2	0.0063	0.0447	0
2,2,4-trimethylpentane	114.2	0.0121	0.0503	0
methylcyclohexane	98.2	0.0000	0.0393	0
2,2-dimethylhexane	114.2	0.0055	0.0207	0
toluene	92.1	0.0550	0.0359	0.1926
2,3,4-trimethylpentane	114.2	0.0121	0.0000	0
3-methylheptane	114.2	0.0000	0.0343	0
2-methylheptane	114.2	0.0155	0.0324	0
n-octane	114.2	0.0013	0.3000	0
2,4,4-trimethylhexane	128.3	0.0087	0.0034	0
2,2-dimethylheptane	128.3	0.0000	0.0226	0
ethylbenzene	106.2	0.0000	0.0130	0
p-xylene	106.2	0.0957	0.0151	0
m-xylene	106.2	0.0000	0.0376	0.1641
3,3,4-trimethylhexane	128.3	0.0281	0.0056	0
o-xylene	106.2	0.0000	0.0274	0
2,2,4-trimethylheptane	142.3	0.0105	0.0012	0
n-nonane	128.3	0.0000	0.0382	0
3,3,5-trimethylheptane	142.3	0.0000	0.0000	0
n-propylbenzene	120.2	0.0841	0.0117	0.1455
2,3,4-trimethylheptane	142.3	0.0000	0.0000	0
1,3,5-trimethylbenzene	120.2	0.0411	0.0493	0
1,2,4-trimethylbenzene	120.2	0.0213	0.0707	0
n-decane	142.3	0.0000	0.0140	0
methylpropylbenzene	134.2	0.0351	0.0170	0
dimethylethylbenzene	134.2	0.0307	0.0289	0.0534
n-undecane	156.3	0.0000	0.0075	0
1,2,4,5-tetramethylbenzene	134.2	0.0133	0.0056	0
1,2,3,4-tetramethylbenzene	134.2	0.0129	0.0704	0.1411
1,2,4-trimethyl-5-ethylbenzene	148.2	0.0405	0.0651	0
n-dodecane	170.3	0.0230	0.0000	0
napthalene	128.2	0.0045	0.0076	0
n-hexylbenzene	162.3	0.0000	0.0147	0.0357
methylnapthalene	142.2	0.0023	0.0134	0
Total		1.0000	1.0000	1.00000

then Figure 8 predicts that ≈ 100 l-air/g-gasoline will be required. This is the minimum amount of vapor required, because it is based on an equilibrium-based model. The necessary minimum average vapor flow rate is then equal to the spill mass times the minimum required vapor flow/mass gasoline divided by the desired duration of venting. Use of this approach is illustrated in the service station site example provided at the end of this paper.

Figure 8 also illustrates that there is a practical limit to the amount of residual contaminant that can be removed by venting alone. For example, it will take a minimum of 100 l-vapor/g-gasoline to remove 90 percent of the weathered gasoline defined in Table 2, while it will take about 200 l-air/g-gasoline to remove the remaining 10 percent. In the case of gasoline, by the time 90 percent of the initial residual has been removed, the residual consists of relatively insoluble and non-volatile compounds. It is important to recognize this limitation of venting, and when setting realistic cleanup target levels, they should be based on the potential environmental impact of the residual rather than any specific total residual hydrocarbon levels. Because mandated cleanup levels are generally independent of the remediation method, this also indicates that soil venting will often be one of many processes used during a given site remediation. It is not difficult to envision that in the future soil venting may be followed or coupled with enhanced biodegradation to achieve lower cleanup levels.

It is appropriate to mention at this point that the mathematical models presented in this paper are being used as "tools" to help plan and design venting system. As with any models, they are mathematical descriptions of processes that at best approximate real phenomena, and care should be taken not to misapply or misinterpret the results.

Are There Likely to Be Any Negative Effects of Soil Venting?

It is possible that venting will induce the migration of off-site contaminant vapors toward the extraction wells. This may occur at a service station, which is often in close proximity to other service stations. If this occurs, one could spend a lot of time and money to unknowingly clean up someone else's problem. The solution is to establish a "vapor barrier" at the perimeter of the contaminated zone. This can be accomplished by allowing vapor flow into any perimeter ground water monitoring wells (which often have screened intervals extending above the saturated zone), which then act as passive air supply wells. In other cases it may be necessary to install passive air injection wells, or trenches, as illustrated in Figure 9a.

As pointed out by Johnson et al. (1988), the application of a vacuum to extraction wells can also cause a water table rise. In many cases contaminated soils lie just above the water table and they become water saturated, as illustrated in Figure 9b. The maximum rise occurs at, or below the vapor extraction well, where the water table rise will be equal to the vacuum at that point

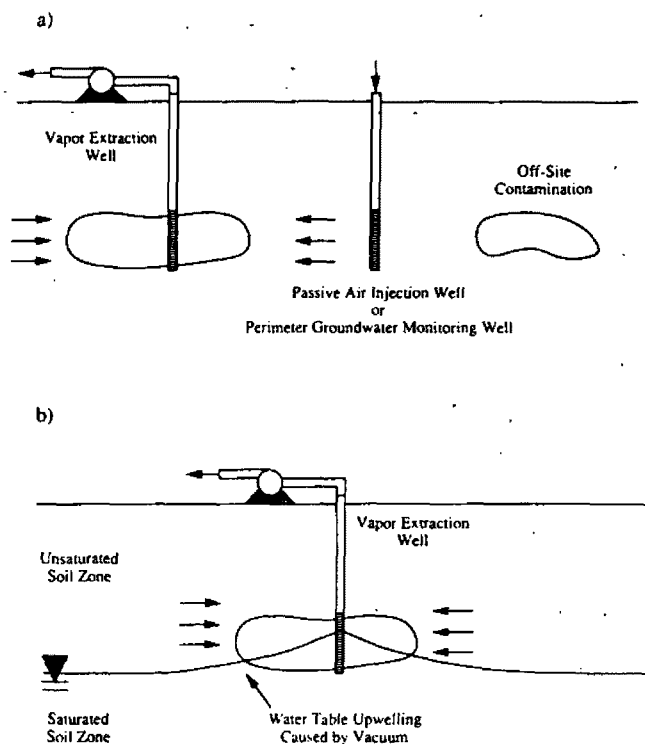


Figure 9. (a) Use of passive vapor wells to prevent migration of off-site contaminant vapors. (b) Water table rise caused by the applied vacuum.

expressed as an equivalent water column height (i.e., in ft H_2O). The recommended solution to this problem is to install a dewatering system, with ground water pumping wells located as close to vapor extraction wells as possible. The dewatering system must be designed to ensure that contaminated soils remain exposed to vapor flow. Other considerations not directly related to venting system design, such as soluble plume migration control and free-liquid product yield, will also be factors in the design of the ground water pumping system.

Design Information

If venting is still a remediation option after answering the questions above, then more accurate information must be collected. Specifically, the soil permeability to vapor flow, vapor concentrations, and aquifer characteristics need to be determined. These are obtained by two field experiments: air permeability and ground water pumping tests, described briefly next.

Air Permeability Tests

Figure 10 depicts the setup of an air permeability test. The object of this experiment is to remove vapors at a constant rate from an extraction well, while monitoring with time the transient subsurface pressure distribution at fixed points. Effluent vapor concentrations are also monitored. It is important that the test be conducted properly to obtain accurate design information. The extraction well should be screened through the soil zone that will be vented during the actual operation. In many cases existing ground water monitoring wells are sufficient, if their screened sections extend above the water table. Subsurface pressure monitoring probes can be

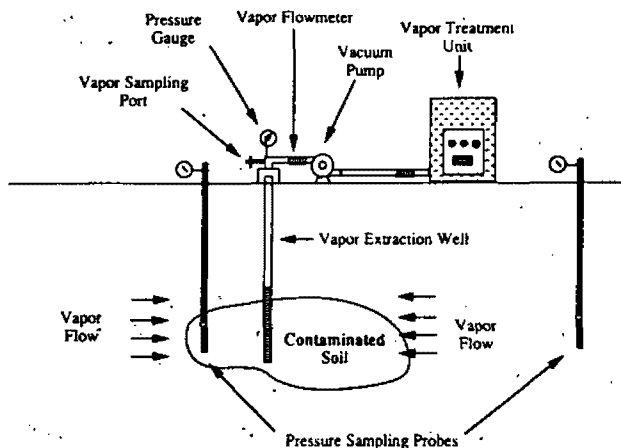


Figure 10. Air-permeability test system.

driven soil-vapor sampling probes (for <20 ft deep contamination problems) or more permanent installations.

Flow rate and transient pressure distribution data are used to estimate the soil permeability to vapor flow. The expected change in the subsurface pressure distribution with time $P'(r,t)$ is predicted (Johnson et al.) by:

$$P' = \frac{Q}{4\pi m(k/\mu)} \int_0^{\infty} \frac{e^{-x}}{x} dx \quad (13)$$

$$\frac{r^2 \epsilon \mu}{4kP_{Atm} t}$$

For $(r^2 \epsilon \mu / 4kP_{Atm} t) < 0.1$ Equation 13 can be approximated by:

$$P' = \frac{Q}{4\pi m(k/\mu)} \left[-0.5772 - \ln \left(\frac{r^2 \epsilon \mu}{4kP_{Atm} t} \right) + \ln(t) \right] \quad (14)$$

Here:

- P' = "gauge" pressure measured at distance r and time t
- m = stratum thickness
- r = radial distance from vapor extraction well
- k = soil permeability to air flow
- μ = viscosity of air = 1.8×10^{-4} g/cm-s
- ϵ = air-filled soil void fraction
- t = time
- Q = volumetric vapor flow rate from extraction well
- P_{Atm} = ambient atmospheric pressure = 1.0 atm = 1.013×10^6 g/cm-s².

Equation 14 predicts a plot of p' -vs- $\ln(t)$ should be a straight line with slope A and y-intercept B equal to:

$$A = \frac{Q}{4\pi m(k/\mu)}$$

$$B = \frac{Q}{4\pi m(k/\mu)} \left[-0.5772 - \ln \left(\frac{r^2 \epsilon \mu}{4kP_{Atm} t} \right) \right] \quad (15)$$

The permeability to vapor flow can then be calculated from the data by one of two methods. The first is applicable when Q and m are known. The calculated slope A

is used:

$$k = \frac{Q\mu}{4A\pi m} \quad (16)$$

The second approach must be used whenever Q or m is not known. In this case the values A and B are both used:

$$k = \frac{r^2 \epsilon \mu}{4P_{Atm}} \exp \left(\frac{B}{A} + 0.5772 \right) \quad (17)$$

Equation 13 can also be used to choose the locations of subsurface pressure monitoring points before conducting the air permeability test, given an estimation of k and the flow rate to be used.

Vapor samples should be taken at the beginning and end of the air permeability test, which should be conducted for a long enough time to extract at least one "pore volume" V_p of vapor from the contaminated soil zone. This ensures that all vapors existing in the formation prior to venting are removed. The vapor concentration at the start of the test is representative of the equilibrium vapor concentration, while the concentration measured after one pore volume has been extracted gives an indication of realistic removal rates and the mixing or diffusional limitations discussed in association with Figure 6. The time τ_p for one pore volume to be removed is:

$$\tau_p = V_p/Q = \epsilon_A \pi R^2 H/Q \quad (18)$$

where R , H , ϵ_A , and Q are the radius of the zone of contamination, vertical thickness of the zone of contamination, air-filled void fraction, and volumetric vapor flow rate from the extraction well. For example, consider the case where $R=12$ m, $H=3$ m, $\epsilon_A=0.35$, and $Q=0.57$ m³/min (20 ft³/min). Then $\tau_p=475$ m³/0.57 m³/min=833 min=14 h.

Ground Water Pumping Tests

To achieve efficient venting, the hydrocarbon-contaminated soil has to be exposed to air flow, which in turn requires that the water table be lowered to counteract the water upwelling effect caused by the decreased vapor pressure in the vicinity of a venting well (Johnson et al. 1988) and to possibly expose contaminated soil below the water table. Thus the ground water pumping system has to have a sufficient pumping rate and be operated for a long enough time period to obtain the required drawdowns. Because most venting systems are installed above phreatic aquifers, two aquifer parameters are needed for the design: average transmissivity T and storage coefficient S . These parameters can be estimated using the results of the standard transient ground water pumping test with a constant pumping rate (Bear 1979). Using the estimated values, the required pumping rate may be calculated as follows:

$$Q = 4\pi T S(r,t)/W(u) \quad (19)$$

where: $W(u)$ is the well function (Bear 1979) of $u = Sr^2/$

4Tt, and $s(r,t)$ is the required drawdown at distance r and pumping time equal to t .

System Design

In this section the questions that must be answered in order to design an in situ soil-venting system will be discussed. It is not the authors' intention to provide a generic "recipe" for soil-venting system design; instead, a structured thought process to guide in choosing the number of extraction wells, well spacing, well construction, etc. is suggested. Even in a structured thought process, intuition, and experience play important roles. There is no substitute for a good fundamental understanding of vapor flow processes, transport phenomena, and ground water flow.

Choosing the Number of Vapor Extraction Wells

Three methods for choosing the number of vapor extraction wells are outlined in the following text. The greatest number of wells from these three methods is then the value that should be used. The objective is to satisfy removal rate requirements and achieve vapor removal from the entire zone of contamination.

For the first estimate residual contaminant composition and vapor concentration changes with time are neglected. The acceptable removal rate $R_{\text{acceptable}}$ is calculated from Equation 4, while the estimated removal rate from a single well R_{est} is estimated from a choice of Equations 2, 6, 7, or 12 depending on whether the specific site conditions are most like Figure 6a, 6b, or 6c. The number of wells N_{wells} required to achieve the acceptable removal rate is:

$$N_{\text{wells}} = R_{\text{acceptable}}/R_{\text{est}} \quad (20)$$

Equations 2, 6, and 7 require vapor flow estimates, which can be calculated from Equation 5 using the measured soil permeability and chosen extraction well vacuum P_w . At this point one must determine what blowers and vacuum pumps are available because the characteristics of these units will limit the range of feasible (P_w, Q) values. For example, a blower that can pump 100 scfm at 2 in. H_2O vacuum may only be able to pump 10 scfm at 100 in. H_2O vacuum.

The second method, which accounts for composition changes with time, utilizes model predictions, such as those illustrated in Figure 8. Recall that equilibrium-based models are used to calculate the minimum vapor flow to achieve a given degree of remediation. For example, if we wish to obtain a 90 percent reduction in residual gasoline levels, Figure 8 indicates that ≈ 100 l-vapor/g-gasoline must pass through the contaminated soil zone. If our spill mass is 1500 kg (≈ 500 gal), then a minimum of 1.5×10^6 l-vapor must pass through the contaminated soil zone. If the target cleanup period is six months, this corresponds to a minimum average vapor flow rate of $0.57 \text{ m}^3/\text{min}$ ($\approx 20 \text{ cfm}$). The minimum number of extraction wells is then equal to the required minimum average flow rate/flow rate-per-well.

The third method for determining the number of

wells ensures that vapors and residual soil contamination are removed from the entire zone of contamination N_{min} . This is simply equal to the ratio of the area of contamination $A_{\text{contamination}}$ to the area of influence of a single venting well πR_1^2 :

$$N_{\text{min}} = \frac{A_{\text{contamination}}}{\pi R_1^2} \quad (21)$$

This requires an estimate of R_1 , which defines the zone in which vapor flow is induced. In general, R_1 depends on soil properties of the vented zone, properties of surrounding soil layers, the depth at which the well is screened, and the presence of any impermeable boundaries (water table, clay layers, surface seal, building basement, etc.). At this point it is useful to have some understanding of vapor flow patterns because, except for certain ideal cases (Wilson et al. 1988), one cannot accurately predict vapor flow paths without numerically solving vapor-flow equations. An estimate for R_1 can be obtained by fitting radial pressure distribution data from the air permeability test to the steady-state radial pressure distribution equation (Johnson et al. 1988):

$$P(r) = P_w \left[1 + \left(1 - \left(\frac{P_{\text{atm}}}{P_w} \right) \right) \frac{\ln(r/R_w)}{\ln(R_w/R_1)} \right]^{1/2} \quad (22)$$

where $P(r)$, P_{atm} , P_w , and R_w are the absolute pressure measured at a distance r from the venting well, absolute ambient pressure, absolute pressure applied at the vapor extraction well, and extraction well radius, respectively. Given that these tests are usually conducted for less than a day, the results will generally underestimate R_1 . If no site-specific data are available, one can conservatively estimate R_1 based on the published reports from in situ soil-venting operations. Reported R_1 values for permeable soils (sandy soils) at depths greater than 20 feet below ground surface, or shallower soils beneath good surface seals, are usually 10m – 40m (Hutzler et al. 1988). For less permeable soils (silts, clays), or more shallow zones R_1 is usually less.

Choosing Well Location, Spacing, Passive Wells, and Surface Seals

To be able to successfully locate extraction wells, passive wells, and surface seals one must have a good understanding of vapor flow behavior. Well locations should be chosen to ensure adequate vapor flow through the contaminated zone, while minimizing vapor flow through other zones.

If one well is sufficient, it should almost always be placed in the geometric center of the contaminated soil zone, unless it is expected that vapor flow channeling along a preferred direction will occur. In that case the well should be placed so as to maximize air flow through the contaminated zone.

When multiple wells are used it is important to consider the effect that each well has on the vapor flow to all other wells. For example, if three extraction wells are required at a given site, and they are installed in the triplate design shown in Figure 11a, this would result

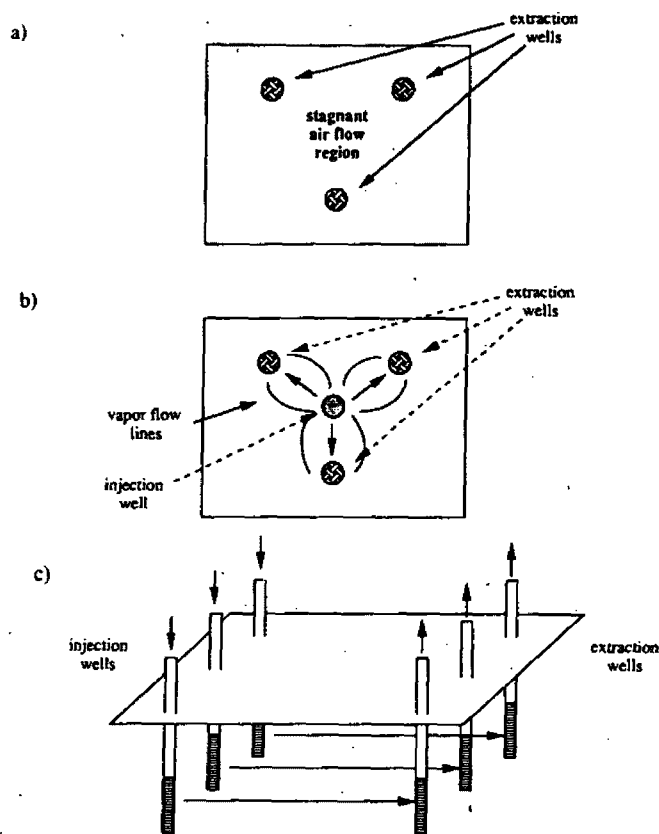


Figure 11. Venting well configurations.

in a "stagnant" region in the middle of the wells where air flow would be small in comparison to the flow induced outside the triplate pattern boundaries. This problem can be alleviated by the use of "passive wells" or "forced injection" wells as illustrated in Figure 11b (it can also be minimized by changing the vapor flow rates from each well with time). A passive well is simply a well that is open to the atmosphere; in many cases ground water monitoring wells are suitable. If a passive or forced injection well is to have any positive effect, it must be located within the extraction well's zone of influence. Forced injection wells are simply vapor wells into which air is pumped rather than removed. One must be careful in choosing the locations of forced injection wells so that contaminant vapors are captured by the extraction wells, rather than forced off-site. To date there have not been any detailed reports of venting operations designed to study the advantages/disadvantages of using forced injection wells. Figure 11c presents another possible extraction/injection well combination. As illustrated in Figure 9, passive wells can also be used as vapor barriers to prevent on-site migration of off-site contamination problems.

For shallow contamination problems (<4m below ground surface) vapor extraction trenches combined with surface seals may be more effective than vertical wells. Trenches are usually limited to shallow soil zones because the difficulty of installation increases with depth.

Surface seals, such as polymer-based liners and asphalt, concrete, or clay caps, are sometimes used to control the vapor-flow paths. Figure 12 illustrates the effect that a surface seal will have on vapor-flow pat-

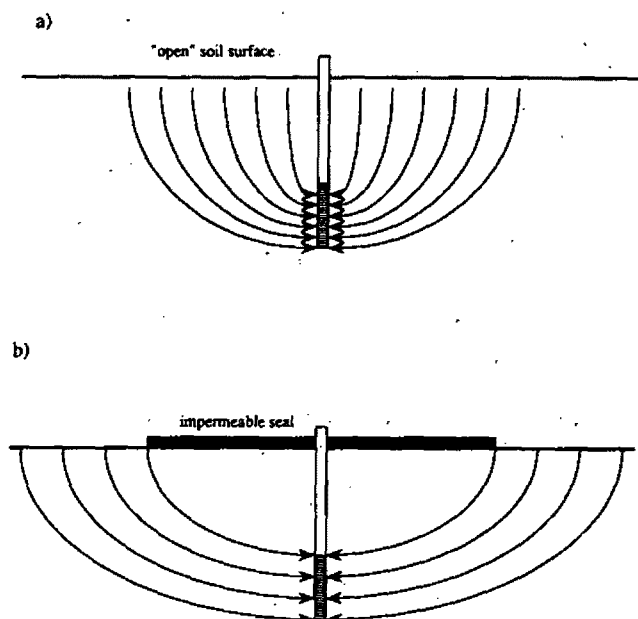


Figure 12. Effect of surface seal on vapor flow path.

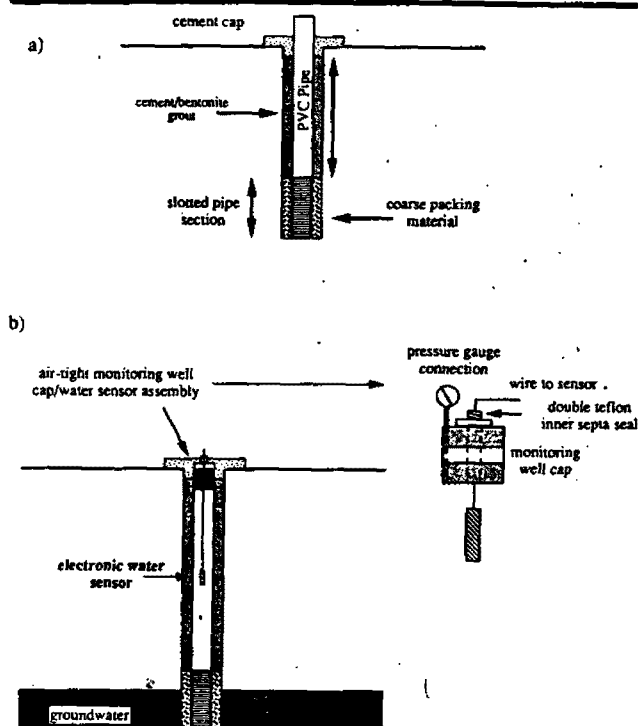


Figure 13. (a) Extraction well construction, and (b) air-tight ground water level measuring system.

terns. For shallow treatment zones (<5m) the surface seal will have a significant effect on the vapor flow paths, and seals can be added or removed to achieve the desired vapor flow path. For wells screened below 8m the influence of surface seals becomes less significant.

Well Screening and Construction

Wells should be screened only through the zone of contamination, unless the permeability to vapor flow is so low that removal rates would be greater if flow were induced in an adjacent soil layer (see Figure 6). Removal rate estimates for various mass-transfer limited scenarios can be calculated from Equations 7 and 12.

Based on Equation 5, the flow rate is expected to

increase by 15 percent when the extraction well diameter is increased from 10cm (4 in) to 20cm (8 in). This implies that well diameters should be as large as is practically possible.

A typical well as shown in Figure 13a is constructed from slotted pipe (usually PVC). The slot size and number of slots per inch should be chosen to maximize the open area of the pipe. A filter packing, such as sand or gravel, is placed in the annulus between the borehole and pipe. Vapor extraction wells are similar to ground water monitoring wells in construction but there is no need to filter vapors before they enter the well. The filter packing, therefore, should be as coarse as possible. Any dust carried by the vapor flow can be removed by an above-ground filter. Bentonite pellets and a cement grout are placed above the filter packing. It is important that these be properly installed to prevent a vapor flow "short-circuiting." Any ground water monitoring wells installed near the extraction wells must also be installed with good seals.

Vapor Treatment

Currently, there are four main treatment processes available:

- **Vapor combustion units:** Vapors are incinerated and destruction efficiencies are typically >95 percent. A supplemental fuel, such as propane, is added before combustion unless extraction well vapor concentrations are on the order of a few percent by volume. This process becomes less economical as vapor concentrations decrease below $\approx 10,000$ ppm_v.
- **Catalytic oxidation units:** Vapor streams are heated and then passed over a catalyst bed. Destruction efficiencies are typically >95 percent. These units are used for vapor concentrations <8000 ppm_v. More concentrated vapors can cause catalyst bed temperature excursions and meltdown.
- **Carbon beds:** Carbon can be used to treat almost any vapor streams, but is only economical for very low emission rates (<100 g/d)
- **Diffuser stacks:** These do not treat vapors, but are the most economical solution for areas in which they are permitted. They must be carefully designed to minimize health risks and maximize safety.

Ground Water Pumping System

In cases where contaminated soils lie just above or below the water table, ground water pumping systems will be required to ensure that contaminated soils remain exposed. In designing a ground water pumping system it is important to be aware that upwelling (draw-up) of the ground water table will occur when a vacuum is applied at the extraction well (see Figure 9b). Because the upwelling will be greatest at the extraction wells, ground water pumping wells should be located within or as close to the extraction wells as possible. Their surface seals must be airtight to prevent unwanted short-circuiting of airflow down the ground water wells.

System Integration

System components (pumps, wells, vapor treating

units, etc.) should be combined to allow maximum flexibility of operation. The review by Hutzler et al. (1988) provides descriptions of many reported systems. Specific requirements are:

- Separate valves, flow meters, and pressure gauges for each extraction and injection well.
- Air filter to remove particulates from vapors upstream of the pump and flow meter.
- Knock-out pot to remove any liquid from vapor stream upstream of the pump and flow meter.

Monitoring

The performance of a soil-venting system must be monitored in order to ensure efficient operation, and to help determine when to shut off the system. At a minimum the following should be measured:

- **Date and time of measurement.**
 - **Vapor flow rates** from extraction wells and into injection wells: These can be measured by a variety of flow meters including pitot tubes, orifice plates and rotameters. It is important to have calibrated these devices at the field operating pressures and temperatures.
 - **Pressure readings** at each extraction and injection well can be measured with manometers or magnahelic gauges.
 - **Vapor concentrations and compositions** from extraction wells: total hydrocarbon concentration can be measured by an on-line total hydrocarbon analyzer calibrated to a specific hydrocarbon. This information is combined with vapor flow rate data to calculate removal rates and the cumulative amount of contaminant removed. In addition, for mixtures the vapor composition should be periodically checked. It is impossible to assess if vapor concentration decreases with time are due to compositional changes or some other phenomena (mass transfer resistance, water table upwelling, pore blockage, etc.) without this information. Vapor samples can be collected in evacuated gas sampling cylinders, stored, and later analyzed.
 - **Temperature:** ambient and soil.
 - **Water table level** (for contaminated soils located near the water table): It is important to monitor the water table level to ensure that contaminated soils remain exposed to vapor flow. Measuring the water table level during venting is not a trivial task because the monitoring well must remain sealed. Uncapping the well releases the vacuum and any effect that it has on the water table level. Figure 13b illustrates a monitoring well cap (constructed by Applied Geosciences Inc., Tustin, California) that allows one to simultaneously measure the water table level and vacuum in a monitoring well. It is constructed from a commercially available monitoring well cap and utilizes an electronic water level sensor.
- Other valuable, but optional measurements are:
- **Soil-gas vapor concentrations and compositions:** These should be measured periodically at different radial distances from the extraction well. Figure 14

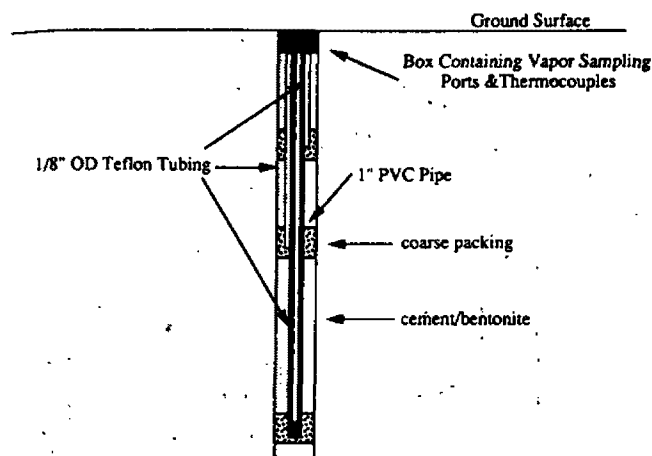


Figure 14. Vadose zone monitoring well installation.

shows the construction of a permanent monitoring installation that can be used for vapor sampling and subsurface temperature measurements. Another alternative for shallow contamination zones is the use of soil-gas survey probes. Data from soil-gas probes are valuable for two reasons: (1) by comparing extraction well concentrations with soil-gas concentrations it is possible to estimate the fraction of vapor that is flowing through the contaminated zone $\phi = C_{\text{extraction well}}/C_{\text{soil gas}}$, and (2) it is possible to determine if the zone of contamination is shrinking toward the extraction well, as it should with time. Three measuring points are probably sufficient if one is located near the extraction well, one is placed near the original edge of the zone of contamination, and the third is placed somewhere in between.

These monitoring installations can also be useful for monitoring subsurface vapors after venting has ceased.

Determining When to Turn Off the System

Target soil cleanup levels are often set on a site-by-site basis, and are based on the estimated potential impact that any residual may have on air quality, ground water quality, or other health standards. They may also be related to safety considerations (explosive limits). Generally, confirmation soil borings, and sometimes soil-vapor surveys are required before closure is granted. Because these analyses can be expensive and often disrupt the normal business of a site, it would be valuable to be able to determine when confirmation borings should be taken. If the monitoring is done as suggested previously, then the following criteria can be used:

- **Cumulative amount removed:** Determined by integrating the measured removal rates (flow rate x concentration) with time. While this value indicates how much contaminant has been removed, it is usually not very useful for determining when to take confirmation borings unless the original spill mass is known accurately. In most cases that information is not available and cannot be calculated accurately from soil-boring data.
- **Extraction well vapor concentrations:** The vapor con-

centrations are good indications of how effectively the venting system is working, but decreases in vapor extraction well concentrations are not strong evidence that soil concentrations have decreased. Decreases may also be due to other phenomena such as water table level increases, increased mass transfer resistance due to drying, or leaks in the extraction system.

- **Extraction well vapor composition:** When combined with vapor concentrations these data offer more insight into the effectiveness of the system. If the total vapor concentration decreases without a change in composition, it is probably due to one of the phenomena mentioned previously, and is not an indication that the residual contamination has been significantly reduced. If a decrease in vapor concentration is accompanied by a shift in composition toward less volatile compounds, on the other hand, it is most likely due to a change in the residual contaminant concentration. For residual gasoline cleanup, for example, one might operate a venting system until benzene, toluene, and xylenes were not detected in the vapors. The remaining residual would then be composed of larger molecules, and it can be argued that these do not pose a health threat through volatilization or leaching pathways.

- **Soil-gas contaminant concentration and composition:** These data are the most useful because it yields information about the residual composition and extent of contamination. Vapor concentrations cannot, in general, be used to determine the residual level, except in the limit of low residual levels (note that Equation 1 is independent of residual concentration). It is important to consider the effect of continued soil-venting system operation on soil-gas sampling results. Results taken during operation, or immediately after shutdown, can be used to assess the spatial extent of contamination and composition of the vapors. After the system is shut down, vapors will begin to migrate away from the source and equilibrate on a larger scale. True soil-vapor concentrations can be measured once equilibrium concentrations are attained in the sampling zone; at least two sampling times will be required to determine that equilibration has occurred. Due to the diffusion of vapors, samples taken after shutdown are not good indicators of the spatial extent of the contaminated zone.

Other Factors

Increased Biodegradation

It is often postulated that because the air supply to the vadose zone is increased, the natural aerobic microbiological activity is increased during venting. While the argument is plausible and some laboratory data are available (Salanitro et al. 1989), conclusive evidence supporting this theory has yet to be presented. This is due in part to the difficulty in making such a measurement. A mass balance approach is not likely to be useful because the initial spill mass is generally not known with sufficient accuracy. An indirect method would be to measure CO_2 levels in the extraction well

vapors, but this in itself does not rule out the possibility that O_2 is converted to CO_2 before the vapors pass through the contaminated soil zone. The best approach is to measure the O_2/CO_2 concentrations in the vapors at the edge of the contaminated zone, and in the vapor extraction wells. If the CO_2/O_2 concentration ratio increases as the vapors pass through the contaminated soil, one can surmise that a transformation is occurring, although other possible mechanisms (inorganic reactions) must be considered. An increase in aerobic microbial populations would be additional supporting evidence.

In Situ Heating/Venting

The main property of a compound that determines whether or not it can be removed by venting is its vapor pressure, which increases with increasing temperature. Compounds that are considered non-volatile, therefore, can be removed by venting if the contaminated soil is heated to the proper temperature. In situ heating/venting systems utilizing radio-frequency heating and conduction heating are currently under study (Dev et al. 1988). An alternative is to reinject heated vapors from catalytic oxidation or combustion units into the contaminated soil zone.

Air Sparging

Due to seasonal ground water level fluctuations, contaminants sometimes become trapped below the water table. In some cases ground water pumping can lower the water table enough to expose this zone, but in other cases this is not practical. One possible solution is to install air sparging wells and then inject air below the water table. Vapor extraction wells would then capture the vapors that bubbled up through the ground water. To date, success of this approach has yet to be demonstrated. This could have a negative effect if foaming, formation plugging, or downward migration of the residual occurred.

Application of the Design Approach to a Service Station Remediation

In the following, the use of the approach discussed previously and outlined in Figure 2, is demonstrated for a service station remediation.

Preliminary Site Investigation

Prior to sampling it was estimated that 2000 gallons of gasoline had leaked from a product line at this operating service station site. Several soil borings were drilled and the soil samples were analyzed for total petroleum hydrocarbons (TPH) and other specific compounds (benzene, toluene, xylenes) by a heated-headspace method utilizing a field GC-FID. Figure 15 summarizes some of the results for one transect at this site. The following relevant information was collected:

- Based on boring logs there are four distinct soil layers between 0 – 18m (0 – 60 ft) below ground surface (BGS). Figure 15 indicates the soil type and location of each of these layers.
- Depth to ground water was 15m, with fine to medium sand soils.

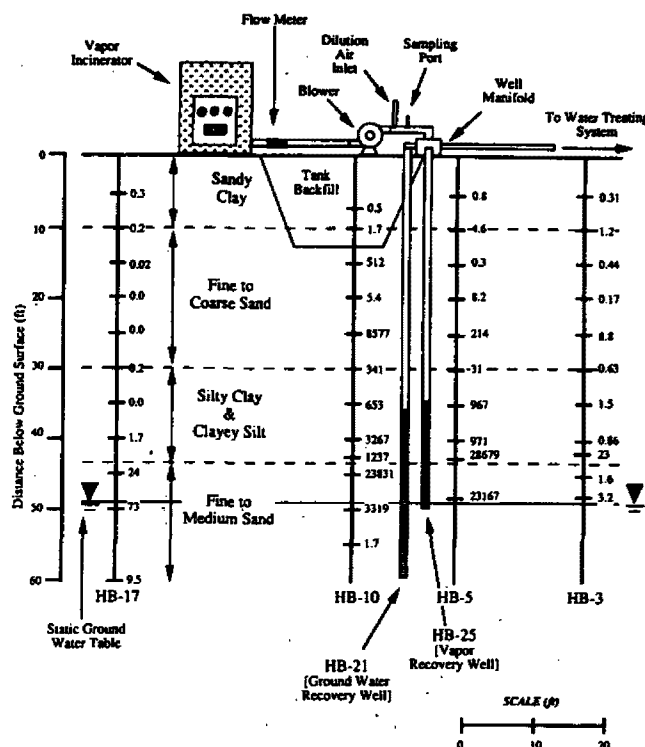


Figure 15. Initial total hydrocarbon distribution [mg/kg-soil] and location of lower zone vent well.

- The largest concentrations of hydrocarbons were detected in the sandy and silty clay layers adjacent to the water table. Some residual was detected below the water table. Based on the data presented in Figure 15 it is estimated that ≈ 4000 kg of hydrocarbons are present in the lower two soil zones.
- Initially there was some free-liquid gasoline floating on the water table: this was subsequently removed by pumping. A sample of this product was analyzed and its approximate composition (≈ 20 percent of the compounds could not be identified) is listed in Table 2 as the "weathered gasoline." The corresponding boiling point distribution curve for this mixture has been presented in Figure 3.
- Vadose zone monitoring installations similar to the one pictured in Figure 14 were installed during the preliminary site investigation.

Deciding if Venting Is Appropriate

For the remainder of the analysis the contaminated soils located just above the water table will be the focus.

- What contaminant vapor concentrations are likely to be obtained?

Based on the composition given in Table 2, and using Equation 1, the predicted saturated TPH vapor concentration for this gasoline is:

$$C_{est} = 220 \text{ mg/L}$$

Using the "approximate" composition listed in Table 2 yields a value of 270 mg/L. The measured soil-vapor concentration obtained from the vadose zone monitoring well was 240 mg/L. Due to composition changes with time, this will be the maximum concentration obtained during venting.

- Under ideal flow conditions is this concentration great enough to yield acceptable removal rates?

Equation 4 was used to calculate $R_{\text{acceptable}}$. Assuming $M_{\text{spill}} = 4000\text{kg}$ and $\tau = 180\text{ d}$, then:

$$R_{\text{acceptable}} = 22\text{ kg/d}$$

Using Equation 2, $C_{\text{est}} = 240\text{ mg/L}$, and $Q = 2800\text{ l/min}$ (100 cfm):

$$R_{\text{est}} = 970\text{ kg/d}$$

which is greater than $R_{\text{acceptable}}$.

- What range of vapor flow rates can realistically be achieved?

Based on boring logs, the contaminated zone just above the water table is composed of fine to medium sands, which have an estimated permeability $1 < k < 10$ darcy. Using Figure 5, or Equation 5, the predicted flow rates for an extraction well vacuum $P_w = 0.90\text{ atm}$ are:

$$0.04 < Q < 0.4\text{ m}^3/\text{m-min} \quad R_w = 5.1\text{cm}, R_l = 12\text{m}$$

$$0.43 < Q < 4.3\text{ ft}^3/\text{ft-min} \quad R_w = 2.0\text{ in}, R_l = 40\text{ ft.}$$

The thickness of this zone and probable screen thickness of an extraction well is about 2m (6.6 ft). The total flow rate per well through this zone is estimated to be $0.08 < Q < 0.8\text{ m}^3/\text{min}$ ($2.8\text{ cfm} < Q < 28\text{ cfm}$).

- Will the contaminant concentrations and estimated flow rates produce acceptable removal rates?

Using $C_{\text{est}} = 240\text{ mg/L}$, the maximum removal rates likely to be obtained are calculated from Equation 2:

$$28\text{ kg/d} < (R_{\text{est}})_{\text{max}} < 280\text{ kg/d.}$$

To be conservative, we will guess that only 50 percent of the vapor actually flows through contaminated soils, so our estimated removal rate per well will be half of these values. The estimated acceptable removal rate $R_{\text{acceptable}} = 22\text{ kg/d}$ falls within this range. Of course this calculation did not take into account the possibility of vapor concentration decreases during venting. This will be taken into account in the next subsection.

- What residual, if any, will be left in the soil?

A target cleanup level for most gasoline spill sites is $<1000\text{ mg/kg TPH}$ residual; in some states the target level is $<100\text{ mg/kg TPH}$. If the initial residual level is $\sim 10,000\text{ ppm}$, then at least 90 percent of the initial residual needs to be removed. According to the curves in Figure 8, which represent the maximum removal rates for the gasoline analyzed at this site, approximately 100 l-vapor/g-residual will have to pass through the contaminated zone to achieve this target. Based on our estimated initial residual of 4000kg TPH, $4 \times 10^8\text{ l-vapor}$ are required. Over a six-month period this corresponds to an average flow rate $Q = 1.5\text{ m}^3/\text{min}$ (54 cfm). Recall that since this corresponds to the maximum removal rate, it is the minimum required flow rate.

- Are there likely to be any negative effects of soil venting?

Given that the contaminated soils are located just above and below the water table, water table upwelling during venting must be considered here.

Air Permeability Test

Figure 16 presents data obtained from the air permeability test of this soil zone. In addition to vapor extraction tests, air injection tests were conducted. The data are analyzed in the same manner as discussed for vapor extraction tests. Accurate flow rate (Q) values were not measured, therefore, Equation 17 was used to

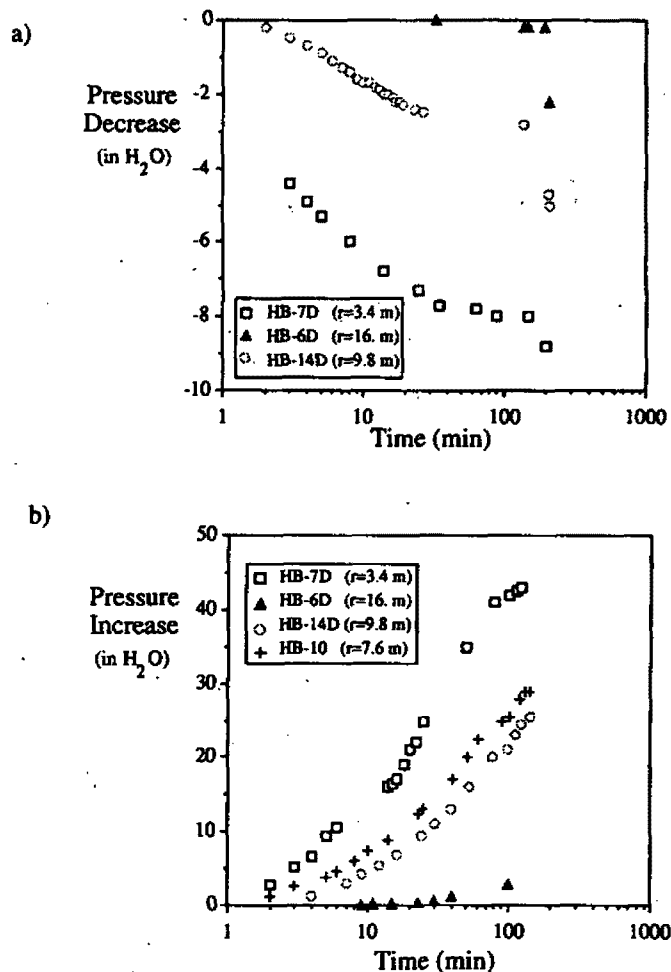


Figure 16. Air permeability test results: (a) vapor extraction test; (b) air injection test. [In H₂O] denote vacuums expressed as equivalent water column heights.

determine the permeability to vapor flow. The k values ranged from 2 to 280 darcys, with the median being ~ 8 darcys.

System Design

- Number of vapor extraction wells:

Based on the 8 darcys permeability, and assuming a 15cm diameter (6 in) venting well, a 2m screened section, $P_w = 0.90\text{ atm}$ (41 in H₂O vacuum) and $R_l = 12\text{m}$, then Equation 5 predicts:

$$Q = 0.7\text{ m}^3/\text{min} = 25\text{ cfm}$$

Based on the preceding discussion, a minimum average flow rate of $1.5\text{ m}^3/\text{min}$ is needed to reduce the residual to 1000 ppm in six months. The number of wells required is then $1.5/0.7 = 2$, assuming that 100 percent of the vapor flows through contaminated soils. It is not likely that this will occur, and a more conservative estimate of 50 percent vapor flowing through contaminated soils would require that twice as many wells (four) be installed.

A single vapor extraction well (HB-25) was installed in this soil layer with the knowledge that more wells were likely to be required. Its location and screened interval are shown in Figure 15. Other wells were installed in the clay layer and upper sandy zone, but in this paper only results from treatment of the lower contaminated

zone will be discussed. A ground water pumping well was installed to maintain a 2m drawdown below the static water level. Its location is also shown in Figure 15.

System Monitoring

Three vadose monitoring wells similar in construction to the one pictured in Figure 14 were installed so that the soil temperature, soil-gas concentrations, and subsurface pressure distribution could be monitored at three depths. One sampling port is located in the zone adjacent to the aquifer. The vapor flow rate from HB-25 and vapor concentrations were measured frequently, and the vapor composition was determined by GC-FID analysis. In addition, the water level in the ground water monitoring wells was measured with the system pictured in Figure 13b. The results from the first four months of operation are discussed in following text

In Figure 17a the extraction well vacuum and corresponding vapor flow rate are presented. The vacuum was maintained at 0.95 atm (20 in H₂O vacuum), and the flow rate was initially 12 scfm. It gradually decreased to about 6 scfm over 80 d. For comparison, Equation 5 predicts that $Q=12$ cfm for $k=8$ darcys. Increasing the applied vacuum to 0.70 atm (120 in H₂O vacuum) had little effect on the flow rate. This could be explained by increased water table upwelling, which would act to decrease the vertical cross section available for vapor flow. The scatter in the flow rate measurements is probably due to inconsistent operation of the ground water pumping operation, which frequently failed to perform properly.

Figure 17b presents the change in vapor concentration with time. Fifteen specific compounds were identified during the GC-FID vapor analyses; in this figure the total concentration of known and unknown compounds detected between five boiling point ranges are presented:

- methane - isopentane (<28 C)
- isopentane - benzene (28 - 80 C)
- benzene - toluene (80 - 111 C)
- toluene - xylenes (111 - 144 C)
- >xylenes (>144 C).

There was a shift in composition toward less volatile compounds in the first 20 days, but after that period the composition remained relatively constant. Note that there is still a significant fraction of volatile compounds present. Within the first two days the vapor concentration decreased by 50 percent, which corresponds to the time period for the removal of the first pore volume of air. Comparing the subsequent vapor concentrations with the concentrations measured in the vadose zone monitoring wells indicates that only $(80 \text{ mg/L})/(240 \text{ mg/L}) \times 100 = 33\%$ of the vapors are flowing through contaminated soil.

Figure 18a presents calculated removal rates (flow rate x concentration) and cumulative amount (1 gal = 3 kg) removed during the first four months. The decrease in removal rate with time is due to a combination of decreases in flow rate and hydrocarbon vapor concentrations. After the first four months approximately one-fourth of the estimated residual has been

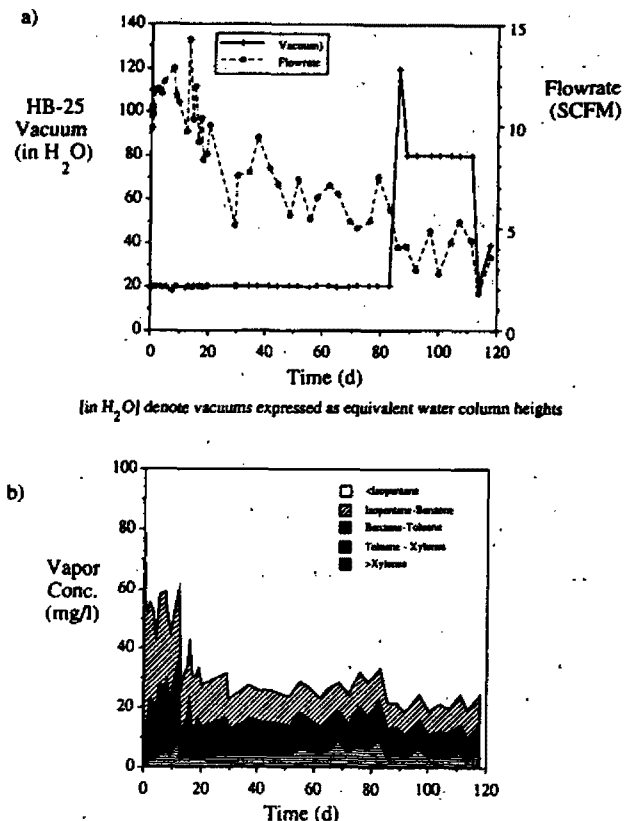


Figure 17. Soil-venting results: (a) vacuum/flow rate data, (b) concentration/composition data.

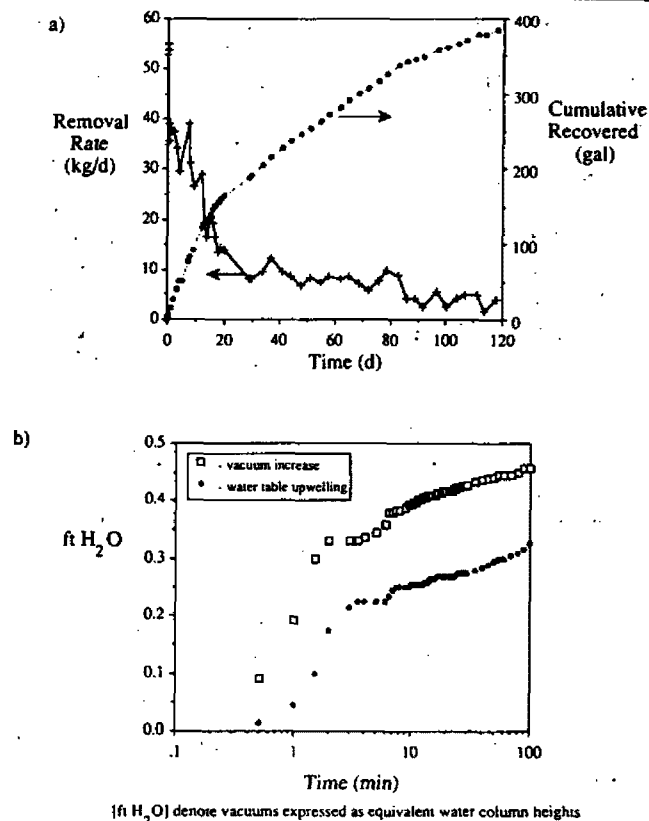


Figure 18. Soil-venting results: (a) removal rate/cumulative recovered, (b) water table rise.

removed from this lower zone.

On day 80 the vacuum was increased from 20 - 120 in H₂O vacuum and the subsequent increase in subsur-

face vacuum and water table upwelling was monitored. Figure 18b presents the results. Note that the water table rise paralleled the vacuum increase, although the water table did not rise the same amount that the vacuum did.

Figure 19 compares the reduced measured TPH vapor concentration $C(t)/C(t=0)$ with model predictions. $C(t=0)$ was taken to be the vapor concentration after one pore volume of air had passed through the contaminated zone ($=80$ mg/L), $m(t=0)$ is equal to the estimated spill mass ($=4000$ kg), and $V(t)$ is the total volume of air that has passed through the contaminated zone. This quantity is obtained by integrating the total vapor flow rate with time, then multiplying it by the fraction of vapors passing through the contaminated zone ϕ ($=0.33$). As discussed, the quantity ϕ was estimated by comparing soil-gas concentrations from the vadose zone monitoring installations with vapor concentrations in the extraction well vapors. There is good quantitative agreement between the measured and predicted values.

Based on the data presented in Figures 15 through 19 and the model predictions in Figure 8, it appears that more extraction wells (≈ 10 more) are needed to remediate the site within a reasonable amount of time (< 2 years).

Conclusions

A structured, technically based approach has been presented for the design, construction, and operation of venting systems. While an attempt has been made to explain the process in detail for those not familiar with venting operations or the underlying governing phenomena, the most effective and efficient systems can only be designed and operated by personnel with a good understanding of the fundamental processes involved. The service station spill example presented supports the validity and usefulness of this approach.

There are still many technical issues that need to be resolved in the future. The usefulness of forced or passive vapor injection wells is often debated, as well as other means of controlling vapor flow paths (impermeable surface covers, for example). A well-documented demonstration of the effectiveness of soil venting for the removal of contaminants from low-permeability soils is also needed. It is clear from the simplistic modeling results presented in this paper that venting will be less effective in such situations. Without a comparison with other viable treatment alternatives, however, it is difficult to determine if soil venting would still be the preferred option in such cases. Other topics for future study include: enhanced aerobic biodegradation by soil venting, the possibility of decreasing residual contaminant levels in water-saturated zones by air sparging/vapor extraction, and optimal operation schemes for multiple vapor extraction well systems.

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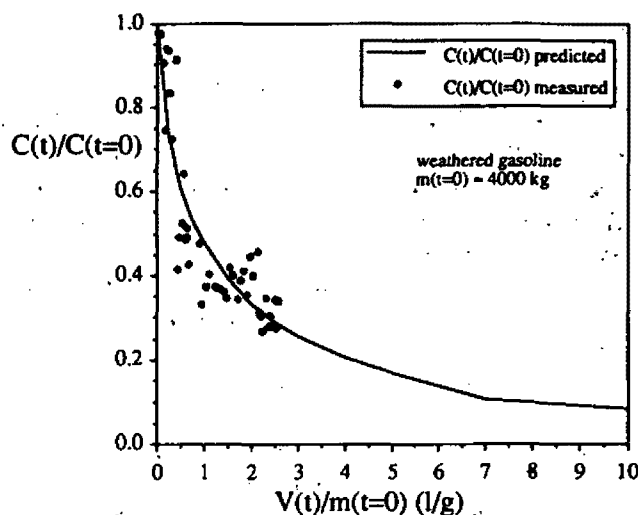


Figure 19. Comparison of model predictions and measured response.

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Biographical Sketches

Paul C. Johnson, Ph.D., joined Shell Development Co.'s (Westhollow Research Center, Room EC-649, P.O. Box 1380, Houston, TX 77251-1380) Environmental Science Department in 1987 after earning his B.S. in chemical engineering from the University of California, Davis, and his Ph.D. in chemical engineering from Princeton University. His current areas of research include the development and evaluation of soil treatment processes, modeling and measuring transport phenomena in porous media, and the development of transport models for predicting emissions and exposures used in environmental risk

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Curtis C. Stanley received his degree in geology with an engineering minor from North Carolina State University in 1979. He is currently a senior hydrogeologist for Shell Oil Co. (Westhollow Research Center, 2236 Two Shell Plaza, Houston, TX 77082) and is responsible for hydrogeologic response at Shell's retail facilities. Stanley is a Certified Professional Geological Scientist and also a Certified Ground Water Professional with the NWWA's Association of Ground Water Scientists and Engineers. He is also a member of API's Ground Water Technology Taskforce and is an EPA Peer Reviewer.

Marian W. Kemblowski, Ph.D., is a senior research engineer in the Environmental Science Department at Shell Development Co. (Westhollow Research Center, Houston, TX 77082) where he has worked since 1985. He obtained his M.S. degree in civil engineering from the Technical University of Warsaw, Poland, in 1973 and his Ph.D. in ground water hydrology from the Institute for Land Reclamation in Warsaw, Poland, in 1978. In 1980 - 1981 he was a visiting hydrologist in the New Mexico School of Mining and Technology. From 1981 to 1985 he worked as an assistant scientist at the University of Kansas. His principal research interests are in the areas of numerical analysis, transport in porous media, and ground water monitoring systems.

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After receiving his B.S. degree in zoology from the University of Nevada, Las Vegas, he was employed by the Texas Water Quality Board as a quality control chemist for 3½ years. In 1977 he joined Shell (Westhollow Research Center, Houston, TX 77082) where he currently is providing technical assistance and support for research in the fate of chemicals in soil and ground water.

James D. Colthart, Ph.D., has been in a variety of R&D and technical planning positions since joining Shell (Westhollow Research Center, Houston, TX 77082) in 1966. He has a B.E. from Yale University and a Ph.D. from Rice University, both in chemical engineering. Currently he is the research manager of Shell Development Co. Air, Waste, and Groundwater Group.

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